THE ACOUSTIC PERFORMANCE OF SUSPENDED CEILING SYSTEMS

By

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In fulfilment

of the requirement for the degree of

Masters of Engineering

University of Canterbury

Christchurch, New Zealand

July 2016

Acknowledgements

I would like to acknowledge those who helped in the preparation of this thesis. Firstly, I thank Associate Professor Dr John Pearse for his guidance as my senior supervisor and for the opportunity to undertake this work. Secondly, I thank Dr Stephen Chiles and Dr Brian Donohue for their guidance and technical assistance. Thirdly, I thank Dr Jeremy Trevathan and my colleagues at Acoustic Engineering Services Ltd for letting me conduct my Masters and bouncing ideas off them.

This work would not have been possible without the assistance of T&R Interior Systems who instigated the construction of the facility which forms the bases of this research. T&R Interior Systems and Potters Interiors supplied ceiling tiles for this research, to both companies, I am grateful.

I would also like to thank my family and friends for their support throughout this work and especially Heather for being patient, supportive, and putting up with my lengthy discussions on ceiling tiles.

Abstract

There are two important acoustic parameters for a suspended ceiling system, sound absorption and the ceiling attenuation class (CAC). The sound absorption of a suspended ceiling system indicates how much of the incident sound is absorbed, whereas the CFN indicates how much sound is transmitted between two adjacent rooms, through the suspended ceiling system and plenum.

The random sound absorption coefficient will be determined using a reverberation room for the front face (the side which faces the room), and the back face (faces into the ceiling plenum) for each ceiling tile product studied.

A CFN facility complying with ASTM E1414-11a was commissioned, and consequently used to determine the transmission loss through the plenum sound path (transmission loss from one room through a suspended ceiling system, across the common ceiling plenum, and down through a suspended ceiling system into the adjacent room) of five ceiling tiles. It was found that as the mass of the ceiling tile increased, the transmission loss increased. This was also seen when acoustic absorption was added to the rear of the ceiling tiles in the plenum. As the mass of the ceiling tile / acoustic absorption increased, the transmission loss increased as per mass law (6 dB increase per doubling of mass).

Table of Contents

List of Figures

List of Tables

List of Graphs

1.0 Introduction

Suspended ceiling systems are commonly employed in commercial and educational spaces and are a major contributing factor to an individual's overall environmental perception and productivity, especially with the widespread adoption of open plan office and large open education spaces. The trend in modern commercial buildings is to construct a suspended ceiling system over the entire floor area, leaving tenants to install separating partitions that only extend from the floor to the height of the suspended ceiling system[1,2]. This method provides a flexible space that can be rearranged to suit the needs of the changing tenants and is more cost effective for the developer to construct[3]. Providing this flexibility can limit the sound transmission between spaces as sound can pass above the wall, via the plenum. The suspended ceiling and plenum (space between the ceiling or roof slab, and the suspended ceiling), has advantages architecturally regarding the installation of illumination and ventilation penetrations and concealing plumbing, ducts, and electrical runs[1,2]. The suspended ceiling and plenum also significantly affect the acoustic properties of the space below, which includes reverberation time control, reducing the transmission of noise between rooms that share a common ceiling plenum, control break-in noise from mechanical systems installed in the plenum, control environmental noise (such as rain noise), and increase speech privacy[4]. Specifying a suspended ceiling system early in the design phase, before tenancy fit-out, usually results in the reverberation time of the room being the only factor considered. Generally, high absorption ceiling tiles do not control sound transmission very well due to the open lightweight structure of the material[5].

Figure 1.1: Installed suspended ceiling in an office building

Open plan classrooms that have multiple teaching spaces within a single large open plan space have become more common in schools in New Zealand and overseas. These are termed Modern Learning Environments (MLE's) or Innovative Learning Environments (ILE) by the Ministry of

Education (MOE)[6]. As with open plan office spaces, a suspended ceiling with a high absorption ceiling tile is usually the only area where absorption is used. While schools and offices usually have different acoustic criteria, this research is relevant to both these spaces.

The amount of sound that is absorbed by a product (in this research a ceiling tile installed in a suspended ceiling grid (termed suspended ceiling system)), will be determined using a reverberation room. This measurement method uses a relatively large sample (between 10 m^2 and 12 m^2), to determine the sound absorption of a product in a diffuse sound field. The tests in the reverberation room enabled the sound absorption on the front face (facing the room), and the back face (facing the plenum) to be determined. The tests on the back face of the suspended ceiling system has been used in predicting whether the ceiling attenuation class (CAC, how much the sound is reduced between rooms though a common ceiling plenum) performance is related to the presence of absorption in the ceiling plenum.

The CAC rating of a suspended ceiling system is the amount of sound attenuated between two rooms when the only significant sound path is through a common ceiling plenum (termed the plenum sound path). To determine the transmission loss (TL) of a suspended ceiling system a ceiling flanking noise (CFN) facility was designed, constructed, and commissioned at the University of Canterbury, which enabled the TL of sound through the plenum sound path between two rooms through a common ceiling plenum to be determined.

Research aims

The main foci of this research was to study the TL through the plenum sound path, and the effect of plenum absorption on this path. This is first explored through the absorption coefficients of the ceiling tile and porous absorber products, and then the TL of a suspended ceiling itself, before considering the TL through the plenum sound path.

The absorption of the back face, and also the absorption coefficient of different porous absorbers were required to be known to determine the current absorption afforded by the back face of the ceiling tiles and the absorption of the products provided in the plenum.

Secondly, the TL was required to be known for each element of the suspended ceiling system to determine the TL of a suspended ceiling to determine if this had any relationship to the TL of the plenum sound path.

Finally, the effect of absorption in the plenum on the TL through the plenum sound path was investigated.

Outline

The acoustic performance of a suspended ceiling system is characterised by two parameters: how much sound is absorbed by the ceiling tiles (Part 1), and the TL (Part 2). The final chapter summarises the conclusions that relates the work to the research aims and describes further research that could be completed.

Part 1 considers sound absorption. The first chapter gives a background and literature review of products used in this research, and current research on absorption products and sound absorption modelling. The second chapter reviews the methodology of conducting sound absorption tests, with the third chapter giving results of the tests following the outlined methodology.

Part 2 considers the TL of the suspended ceiling elements. The first chapter in this part gives a background and literature review of current trends on the TL of suspended ceiling systems, and how tests are conducted in a standard TL facility and in a CFN facility. Chapter 5 reviews the relevant standards on CFN facilities, and the commissioning of the CFN facility at the University of Canterbury. Chapter 6 reviews the methodology of conducting TL tests in both facilities. The final two chapters in this part outline the results from the measurements conducted in the TL facility and CFN facility results.

The final chapter concludes the research conducted within this research describing the effect absorption in the plenum in the TL of the plenum sound path. The increase in TL through the plenum sound path is also discussed. This chapter ends with further research that could be conducted in line with this research, and further work that could be made using a CFN facility.

2.0 Background and Literature Review – Porous Absorbers

2.1 Overview

The acoustic performance of a suspended ceiling system is typically described by two parameters. The first is the absorption coefficient, which relates how much energy is absorbed (transferred into heat energy) by a product when sound is incident upon it. The second parameter is the ceiling attenuation class (CAC), which describes the reduction of sound when it is transferred from one room into a ceiling plenum, then from the plenum into an adjacent room through the suspended ceiling system (plenum sound path). This chapter focuses on porous absorbers, specifically ceiling tiles. The reduction in sound through the plenum sound path is considered in Chapter 5.

This chapter provides an overview on the mechanism that porous absorbers absorb sound, the acoustic rating of products, and previous research on the sound absorption provided by ceiling tiles, including prediction models, and product reviews. This research is primarily based on ceiling tiles, and the associated suspended ceiling grid (together called a suspended ceiling system), however bulk panel porous absorbers (called porous absorbers) are also reviewed as ceiling tiles would be considered a sub-category of these. This section provides a basis for the experimental work described in the subsequent chapters.

2.2 Absorption mechanism

2.2.1 Structure of a porous absorber

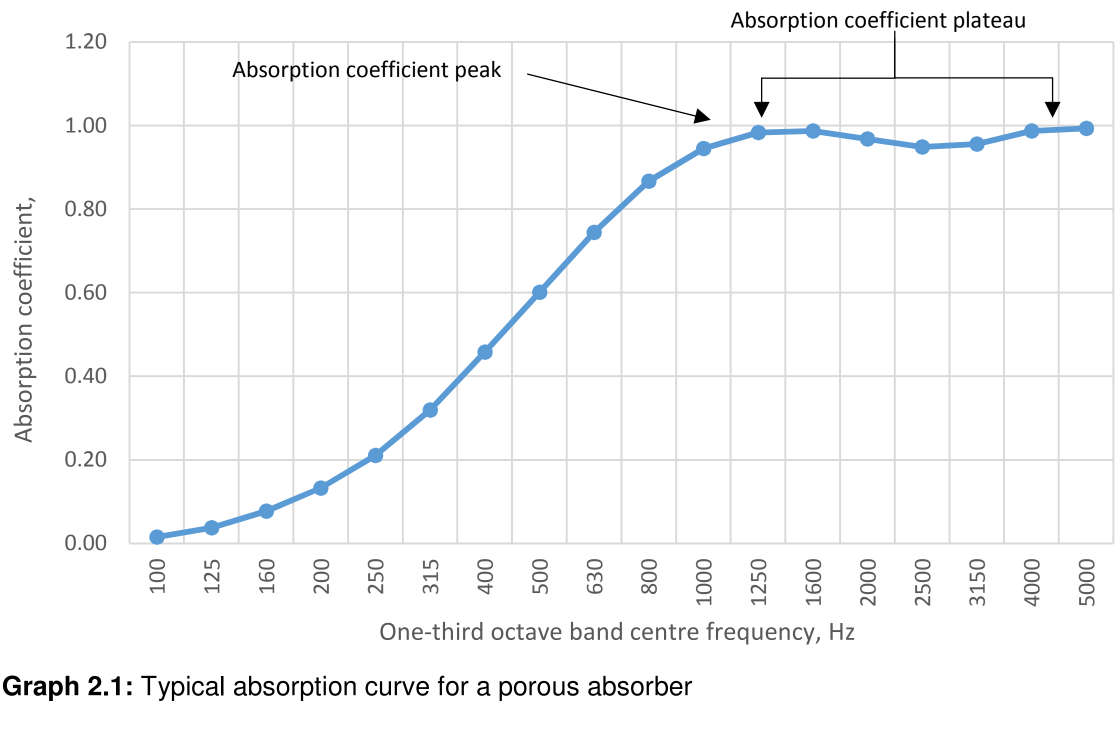
A porous absorber is a product that is made from many interlocking pores or fibres that sound waves are able to enter[7]. The structure of a porous absorber can be divided into two parts; the solid part (the structure of the fibres themselves), and a liquid part (usually the air that surrounds the fibres). To 'absorb' sound, the fibres need to come into contact with the air external to the product, so that the acoustic energy can propagate though the product[8]. Therefore, the number of fibres that are open to the outside is a determining factor in the amount of sound absorbed by a product[9]. The product of the solid part of a porous absorber can vary significantly from cloth-like cotton, to open-cell foams, glass fibres, polyester, and even straw.

This work is concerned with fibrous porous absorbers. Fibrous absorbers are differentiated from other types of porous absorbers (cellular and granular) by a network of interlocking microscopic fibres that are intertwined to hold the product together in a rigid structure. Ceiling tiles can often be classified as fibrous porous absorbers as they are usually made from mineral fibre, which has been manufactured similar to fibrous porous absorbers however are compressed.

2.2.2 Sound absorption

When sound waves are incident on the fibres of a fibrous porous absorber, the sound energy is converted into heat energy due to friction at high frequencies, and heat exchange at low frequencies[10], as energy cannot be created or destroyed. This is the mechanism by which the product 'absorbs' sound. The amount of sound absorption that a product provides relates to how efficiently a product converts the sound energy into heat.

The performance of a porous absorber is defined by multiple parameters including fibre diameter, porosity, and flow resistance. These properties are used in empirical formulae to predict the sound absorption, as discussed in Chapter 3. The performance of a porous absorber is also a product of the wavelength of sound that is incident upon the product. Therefore the absorption is frequency dependant. At low frequencies, porous absorbers tend not to absorb as well as at high frequencies. A typical absorption coefficient curve is shown in Graph 2.1.



Graph 2.1: Typical absorption curve for a porous absorber

2.3 Acoustic rating of sound absorbing products

The parameter that defines how well a product absorbs sound is called the absorption coefficient; the ratio, at each frequency, of the sound intensity absorbed compared the sound intensity reflected. As this parameter is a ratio, a perfect reflector (a product that does not absorb any sound) has an absorption coefficient of 0, while a perfect absorber has an absorption coefficient of 1.

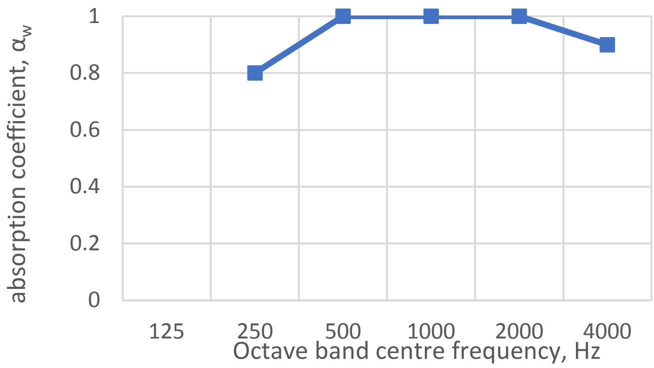
Single number acoustic absorption ratings are given to products to facilitate a quick comparison between products. The single number ratings are defined in ISO 11654:2002[11] (weighted sound absorption coefficient (α_w)) and ASTM C423-09a[12] (Sound Absorption Average (SAA)).

2.3.1 Single number ratings

SAA rating is defined in the latest ASTM C423-09a standard and replaces the previously used NRC rating in ASTM C423-07a[13]. The SAA is calculated by averaging the sound absorption coefficients at each one-third octave band centre frequency between 200 Hz and 2,500 Hz inclusive. The SAA is rounded to the nearest 0.01.

The NRC rating was previously calculated by averaging the absorption coefficients of the octave band centre frequencies between 250 Hz – 2,000 Hz inclusive.

The weighted sound absorption coefficient, α_w, described in ISO 11654:2002 is calculated by fitting the reference curve (shown in Graph 2.2) to the average octave band absorption coefficients between 250 Hz and 4,000 Hz, such that the sum of the unfavourable deviations is less than or equal to 0.10.



Graph 2.2: Reference curve for calculation of the weighted sound absorption coefficient, α_w [11]

2.4 Absorption of ceiling tiles

Ceiling tiles can be classified into three types: porous tiles, mineral fibre tiles, and composite tiles. A section through the three different ceiling tile products is shown in Figure 2.1 below.

Figure 2.1: Section through porous, mineral fibre, and composite ceiling tiles

2.4.1 Porous ceiling tiles

Porous ceiling tiles are typically constructed of glass fibre or polyester sheets, and have a relatively high acoustic absorption rating. Porous ceiling tiles are generally used in open plan spaces (typically open plan schools), where acoustically there is only a requirement for absorption within the space. Generally in this application, the ceiling will be the most significant absorbing surface. Due to the high absorption coefficient of porous ceiling tiles, they reduce the noise build—up within the space, increase the speech transmission index, and increase speech privacy.

2.4.2 Mineral fibre ceiling tiles

Mineral fibre ceiling tiles are constructed of compressed mineral fibre, which have a similar open structure to porous ceiling tiles. However due to the compressed nature of the product, they generally have lower absorption ratings than porous ceiling tiles. Mineral fibre ceiling tiles are generally used in smaller spaces, where there is the potential for spaces to be broken up into smaller spaces, or where the separating walls are constructed only as high as the suspended ceiling. These tiles typically attenuate noise in the plenum sound path better than porous ceiling tiles. This is discussed further in later chapters. This ceiling tile type is the most common in commercial office spaces.

2.4.3 Composite ceiling tiles

Finally, composite ceiling tiles have a porous absorber facing the room and a high mass backing material adhered to the porous absorber, usually plasterboard. Composite ceiling tiles are used in applications where a high absorption product is needed in the space along with the capability for reducing noise between adjacent spaces, or noise from other locations (mechanical plant located in the plenum, environmental noise, etc.). The porous absorbers allow the ceiling tile to have a high absorption and the high mass backing reduces sound propagation through the ceiling tile.

2.4.4 Commercially available information and products

Mineral fibre ceiling tiles are the most commonly used ceiling tile, followed by porous fibreglass ceiling tiles. Commercially available mineral fibre ceiling tiles come in a range of thicknesses, surface finishes, and acoustic ratings. They can also be sealed to ensure they meet hygiene requirements in healthcare applications, or coated with hydrophobic material so they do not get damaged in high humidity environments. Porous ceiling tiles are generally limited to increasing the absorption within the space, rather than reducing sound between spaces.

Mineral fibre and porous ceiling tiles generally have a facing tissue adhered to the front face (facing into the room), which provides an aesthetic finish to the ceiling tile. This facing should be acoustically transparent to ensure that the sound waves penetrate into the absorbing medium behind. These finishes can come in many colour shades, and can be laser printed to any pattern to match the aesthetics of the space. Ceiling tiles generally also have sealant coats, glue and other additives to the mineral fibre.

Currently, the only information of the sound absorption (sound absorption coefficient) that is provided by manufacturers is measured in a reverberation room, with the front face facing into the room (on occasion, with an air cavity behind). While this gives accurate absorption coefficients of the front face of the ceiling tile, the absorption coefficient of the back face, facing into the plenum is not provided. Due to sealants and coatings that are used on the sides and back face of the ceiling tile, the absorption coefficient cannot be assumed to be the same as for the front face. No documented research into the absorption coefficient of the back face of ceiling tiles has been found. While this was expected, the absorption of the ceiling tiles back face will provide additional absorption within the cavity, which is hypothesised to increase the transmission loss between rooms through a common plenum.

2.5 Theoretical acoustic absorption prediction models

There are two different models to predict the absorption of a porous products that are widely used: the empirical models developed by Delany and Bazley, and the theoretical models developed by Allard and Champoux[14]. The empirical models appear less complex and need fewer inputs, and so are easier to construct, the theoretical models are more complex.

The products material properties that need to be determined in order to predict the sound absorption of a porous absorber are split into two categories; macrostructure and microstructure. The macrostructure of a porous product is reflected in the flow resistivity, porosity, and skeleton elasticity[10]. The microstructure of a porous product that is taken into account is the specific shape and size of the pores, the product that the product is made from (glass fibre, polyester, sheep wool), length of the fibres, and the tortuosity[10].

The empirical models developed by Delany and Bazley are based on measured normal absorption coefficients and other material properties of products that determine the structure of the product. Delany and Bazley compiled a large amount of measured acoustical properties of porous absorbent products. From the measurements it was found that power laws could be used to model the measured results. From the power laws, impedance and sound propagation constants were used to predict the normal incidence absorption coefficients of rigidly backed absorbers. The model by Delaney and Bazley is the most popular as the flow resistance of a product is the only factor that is required to be known to calculate the sound absorption of the product[10]. This model also is used in the calculation methods outlined in EN 12354-6:2003 *Building Acoustics – Estimation of acoustic performance of buildings from the performance of elements – Part 6: Sound absorption in enclosed spaces*[10, 15].

Bies and Hansen also carried out an in-depth study, extending the work of Delany and Bazley. Their research concentrated on the effect of flow resistance on the prediction of absorption coefficients[14]. It was found from this research that the product's flow resistance was the most important input to characterise a products absorption. Bies and Hansen presented an empirical model that predicted the flow resistivity of a product based on the fibre diameter and density of fibres within the product. From this, the power laws developed by Delany and Bazley were used to predict the absorption coefficients at normal incidence. From established acoustic models, the statistically averaged absorption coefficients were calculated to give absorption coefficients more in agreement with those measured in a reverberation room. However the predicted random incidence absorption coefficients, calculated from the predicted normal absorption coefficients still differed significantly from those measured in a reverberation room[10].

Theoretical models (to predict more accurately the sound propagation in fibrous materials) were developed by Allard and Champoux, and were be able to make more accurate predictions of the absorption coefficients of the products at different frequencies. These equations are purely theoretical and are based on how the viscous forces in porous materials change with frequency. At low frequencies where Delany and Bazley's models are less accurate, the equations developed by Allard and Champoux provide a better agreement with measured results [14, 16].

Ingard carried out an in-depth investigation into the theoretical modelling of absorption. This study showed similarities to Bies and Hansen's work that found that the frequency dependant absorption coefficient was predominantly determined by the flow resistivity and thickness of the product. Ingard also found that the properties of porosity and structure (fibre diameter, and density of the fibres within the product) of a product had a small effect on the absorption coefficients and could be used to calculate the flow resistance of porous products.

The Biot theory of sound propagation is one of the oldest theories for predicting sound absorption within a product, and is also the most detailed. The Biot model predicts the longitudinal sound waves travelling though the liquid, longitudinal sound waves travelling through the solid part, and shear sound waves travelling through the solid part. The material properties needed for determining the interaction between these three waves and the product are the air flow resistivity, tortuosity, thermal characteristic length, viscous characteristic length, and porosity[17,18].

All these models predict the normal absorption coefficients of a product, whereas measurements undertaken in a reverberation room determine the random acoustic absorption coefficients of a product. Comparisons of the predicted normal absorption coefficients and random absorption coefficient show they are not comparable. London[19], as far back as 1949, has been predicting the random incidence absorption coefficient from predicted normal incidence absorption coefficients. This has been further refined by Muller-Trapet *et al*[20], McGroy *et al*[21], and others, with some success. However, all normal incidence to random incidence models give different results to the measured data obtained from measurements in a reverberation room.

2.6 Analysis of absorption coefficient measurements

There are two methods that can be used to determine the absorption coefficient of a porous products. These are either using a relatively large sample in a reverberation room, or a relatively small sample in an impedance tube.

2.6.1 Normal incidence absorption measurements

The impedance tube measures the absorption coefficients of a product at normal incidence, using the standing wave methodology. The principle of the standing wave method to measure and calculate the acoustic absorption of a product is based on measuring the amplitude of the sound wave reflected back by the product compared to that incident upon the product. The sound wave is perpendicular to the products surface, so absorption at other angles is not taken into account. This is a much more controlled measurement, as only one angle of incidence, and often only one frequency is measured at a single time.

2.6.2 Random incidence absorption measurements

A reverberation room is used to determine the absorption coefficients of a product at random incidence, where all angles of sound waves incident on the product are taken into account. Laboratory measurements of random incidence absorption has been found to have a better relationship with field measurements than those of normal incidence sound absorption measurements.

A large room that has hard, reflective surfaces is used for these measurements, with multiple diffusion panels within the room that ensure that the room is sufficiently diffuse, such that all sound is travelling at equal magnitude and probability in all directions. To measure the sound absorption afforded by a product, a sound source produces a high level of sound within the room, which is then cut. The time taken for the sound to decay by 20 dB and 30 dB is measured and the time to decay by 60 dB is usually obtained by extrapolation. This is done with and without the product in the room. The difference in the reverberation times is used to calculate the absorption coefficient of the product[12, 22]. This is described further in Chapter 3.

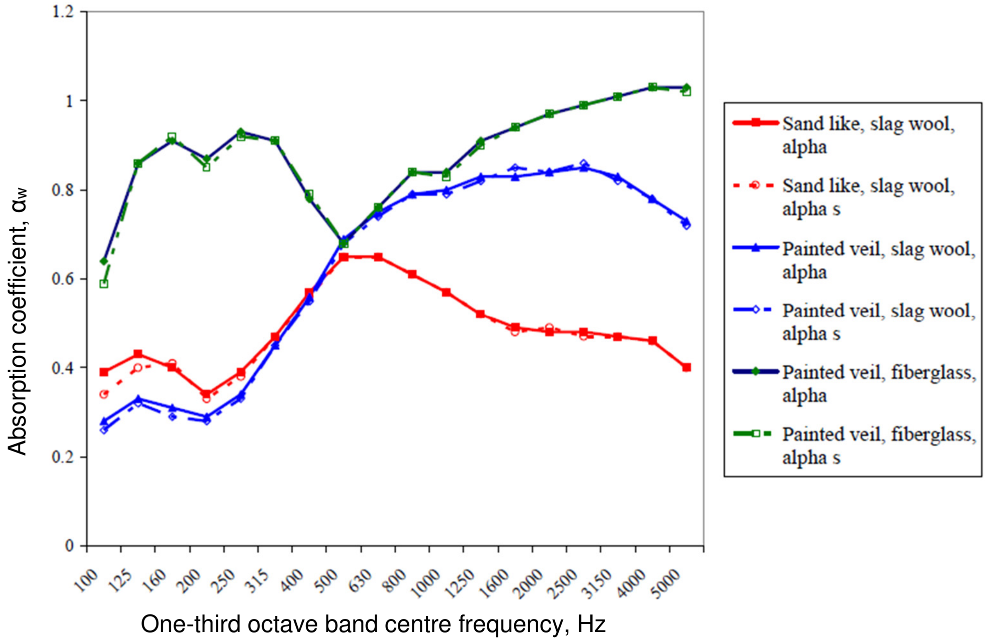
2.6.3 Measurement repeatability

There have been multiple studies of the reproducibility of random incidence absorption coefficients at different laboratories[23,24,25,26,27]. Many of the differences that are seen between laboratories are put down to differing dimensions, volume or placement of diffusing panels[28,29]. Additional differences have been put down to lack of diffuseness in the reverberation room[30,31,32,33,34], which affects the assumptions in the calculations.

In addition to laboratory differences, inconsistent measurement methodology also affects the absorption coefficients measured. Both commonly used standards for measuring absorption coefficients require, as best practice, the sides of the absorption product to be covered with a reflective surface, ideally steel. If the sides are not covered, sound can be absorbed along them, and due to the product being thick when viewed from the side, can lead to large absorption at low frequencies, which wouldn't occur in practice. This is called the *edge-effect* and has been widely documented[35,36].

2.6.4 Difference in measurement methodology

Beschel *et al* measured the absorption coefficient of products using the ASTM and ISO measurement procedures individually to determine the difference in absorption coefficients. They concluded that there is very little difference between the two methods[37]. Graph 2.3 below shows the difference between a slag wool and fibreglass product measured to both the ASTM and ISO standard. It shows, (apart from the 160 Hz and 200 Hz for the fissured slag wool) that the measurements are comparable and within the recommended margin of error. It is concluded that whichever method is used the SAA or α_w rating can be calculated[37].

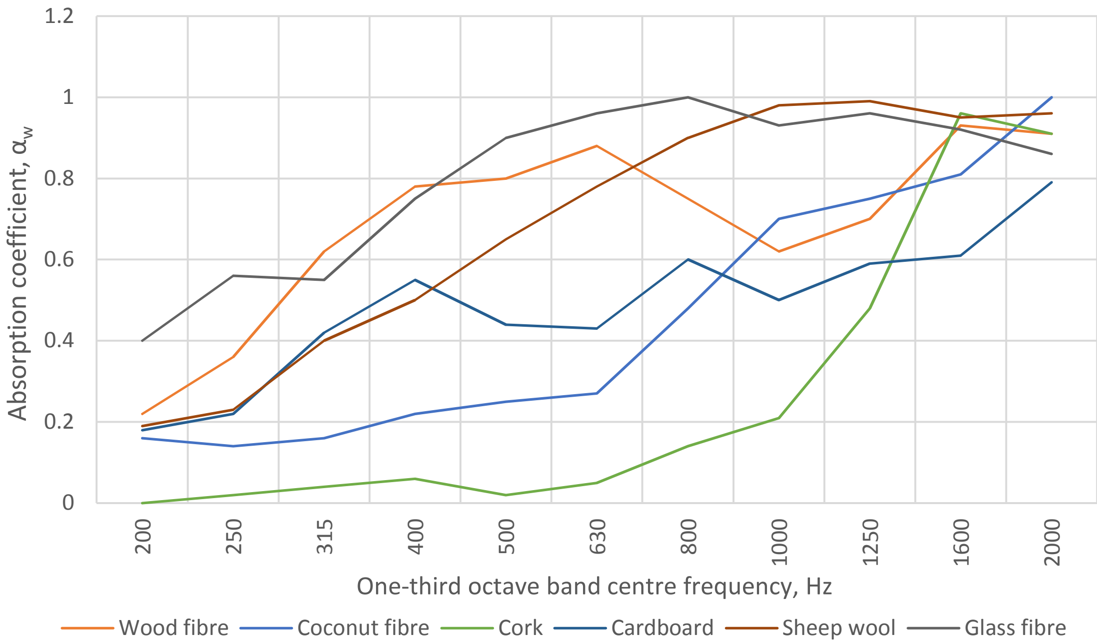


Graph 2.3: Comparison between ASTM C493 and ISO 354 absorption measurements for two slag wool and one fibreglass product[37]

Beschel *et al*[37] calculated the single number rating for each product in accordance with each standard. Due to the weighting curve being negatively sloping in the high frequencies, flat in the mid frequencies, and a negatively sloping in the low frequencies, the α_w rating is always the same or lower than the SAA (or NRC) rating, which is calculated by the average octave band absorption coefficients[37]. The α_w rating allows for a L, M, or H suffix at the end of the product which corresponds to whether the absorption coefficient of the product is higher at the low, medium, or high frequencies than that represented by the single number α_w rating[37].

2.7 Current trends in porous absorbers

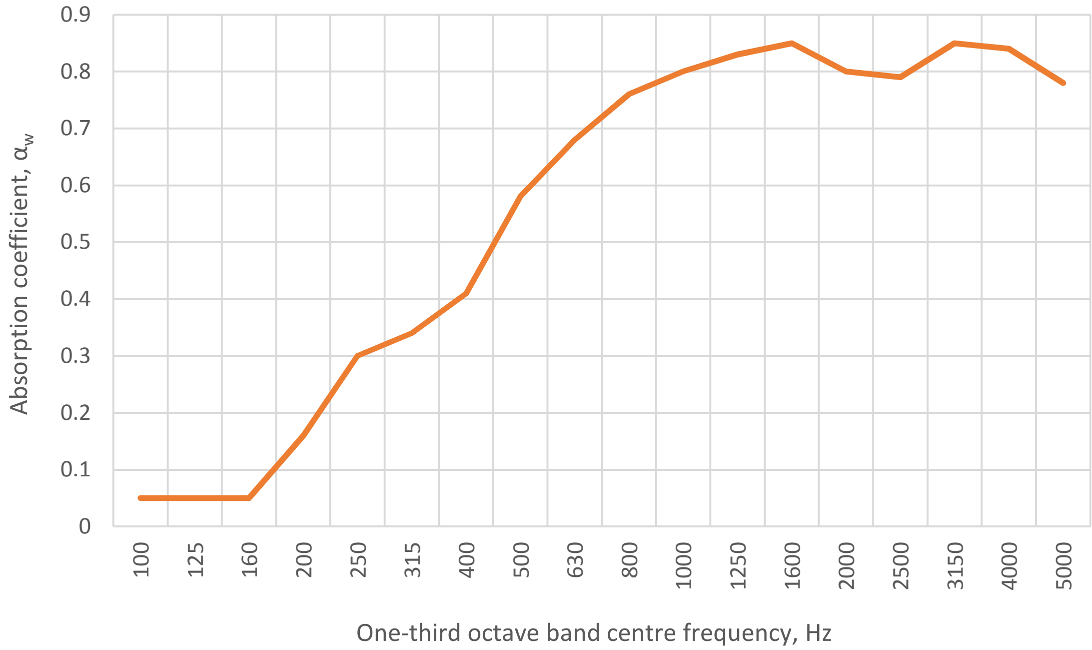
Due to the heightened awareness of climate change and the movement towards sustainable materials, there has been many recent studies into sustainable or recycled acoustic absorption products. In addition, while glass fibre and Rockwool are not known to be hazardous, it is standard practice to wear full safety equipment including breathing apparatus when installing or handling these products[38]. With natural, sustainable products, this is not needed. A product can be considered sustainable if the resources from which the product is derived, continues to be available for future generations[39]. These materials mostly come from plants, animals, or earthen materials, which include sheep wool, cork, expanded clay, flax, cotton, and coconut fibre. Iannace[40] measured the absorption coefficient of nine different 'sustainable' materials in an impendence tube (normal incidence sound absorption), and the flow resistivity of the materials. The measurements that Iannace measured are shown in Graph 2.4[40], with the normal incidence sound absorption coefficient of glass fibre also modelled to show correlation between these sustainable materials and current absorption materials.



Graph 2.4: Selection of normal incidence sound absorption coefficients of sustainable absorption materials[40]

It was found that many 'sustainable' materials have similar absorption coefficients to current common porous absorption products on the market, especially sheep wool and wood fibre. As with common porous absorption products, the majority of these products have high absorption coefficients at mid-to-high frequencies, with poor absorption at low frequencies. It was found in the same study that to increase absorption at low frequencies, an increase in thickness was needed, as with common porous absorbers[40].

Sheep wool in particular has been widely researched for its thermal and acoustical properties. Many papers report on the absorption measurements on different thicknesses of sheep wool and compositions of wool and polyester, as sheep wool can vary depending on the breed, location of wool on the sheep's body, condition of the sheep and environmental conditions, and also on how the wool is processed. Bosia[41] reports on measurements for 50 mm wool that consisted of off cuts of wool that were not high enough quality for the yarn, weaving, or other industries. These measurements are shown in Graph 2.5 below, and have an overall weighted random incidence sound absorption coefficient of α_w 0.55 (MH). This specimen shows performance as for a typical porous absorber[41].



Graph 2.5: Sound absorption measurements of low quality sheep wool blankets[41]

It can be seen from Graph 2.5, as well as examining previously measured absorption coefficients of sheep wool[39,40,38], that acoustically, wool can be competitive against standard glass fibre or polyester absorption products.

Ballagh[38] completed an in depth study on how different densities, fibre diameters and flow resistivity affected the absorption coefficient of a wool absorption product. From Ballagh's study, it was found that increasing the density of the wool whilst keeping the thickness equal increased the absorption coefficient until it reached an optimum density. An increase in density past this optimum point, reduced the absorption coefficient[38]. Ballagh found that wool had a relatively large fibre diameter compared to that of other fibrous products (between 22 μm and 35 μm), and determined the absorption coefficient for three different fibre diameters, which had similar flow resistivity and densities. Ballagh found that, as typical of porous absorbers, a decrease in fibre diameter, increased the absorption coefficients. It was found that in the mid frequencies, the absorption coefficient increased by 0.1 for each 6 μm decrease in fibre diameter[38].

Finally, Ballagh[38] measured the flow resistivity of various wool porous absorbers to determine a relationship between the density and flow resistivity of a wool sample. The products had an average fibre diameter of 22, 28, 29, and 35 μm with differing densities between 13 kg/m^3 to 90 kg/m^3. It was found that the flow resistivity of the wool samples measured was inversely proportional to the fibre diameter. The following statistical relationship was found for the wool samples measured

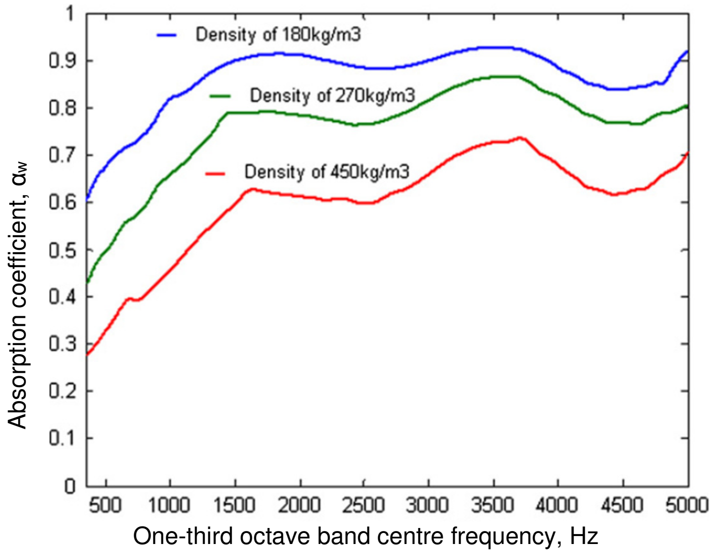
$$\sigma = 490\frac{\rho^{1.61}}{d} \qquad \text{Equation 1.1}$$

Where σ is the flow resistivity, ρ is the density of the product, and d is the average fibre diameter of the sample.

In addition to natural sustainable materials, research into recycling of end-of-life products into acoustic absorbers has been gathering momentum, due to the need to reduce waste to landfills. Because of the large quantities of rubber tyres that are currently either incinerated or disposed of, substantial research has gone into recycling these products. Acoustically, research has focused on using the rubber crumbs produced during the recycling process as granular porous absorbers, and using the recycled tyre 'fluff' as a fibrous absorption product[42].

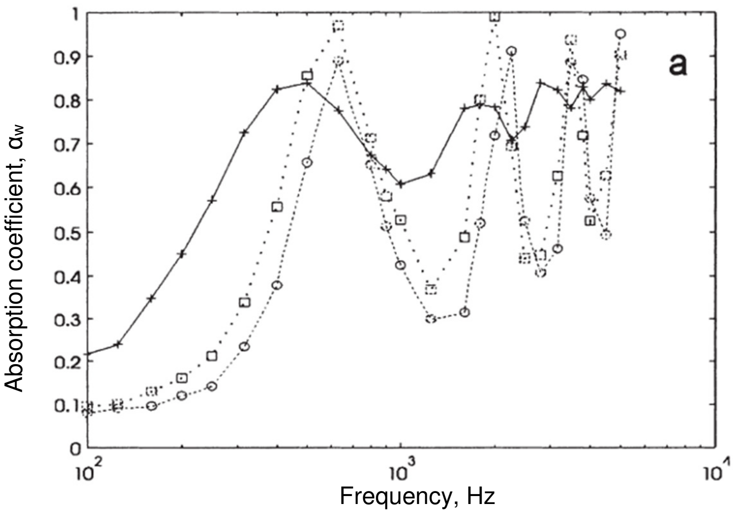
There are three products that generally make up tyres: steel, rubber, and textile. Generally recycling the steel and rubber is done efficiently, with the textile 'fluff' being discarded. Jimenez-Espadafor *et al*[43] measured the acoustical and mechanical properties of the tyre fluff from car tyres in an attempt to develop a ceiling tile that would fit into an existing 600 mm x 600 mm suspended ceiling grid. The tyre fluff was added to a hot-melt adhesive to bind the tyre fluff together[43].

From this study[43], it was found that a density of tyre fluff between 180 kg/m^3 and 250 kg/m^3 was optimal, as this gave the highest acoustic absorption coefficients. It was also found that when screened for size, a 5 – 8 mm size was optimum for allowing sufficient voids for absorption, but not too small to allow the fibres to compress thus reducing the absorption coefficient. Graph 2.6 below shows the absorption coefficient of 80 mm thick tyre fluff acoustic absorption product at different densities. The sample at 180 kg/m^3 had the highest absorption coefficient. It is interesting to note that the absorption coefficient rises like a typical porous absorber until approximately 1,400 Hz. The absorption coefficient then plateaus, as with a typical porous absorber, but then increases around 3,700 Hz, which is more prevalent in higher density samples. This may be due to the adhesive used acting as a resonant absorber at this frequency, as the more solid the structure, the better this absorption resonance would be[43]. From the Jimenez-Espadafor *et al* research, it was found that an absorption layer and a secondary dense layer was needed to ensure that the proposed ceiling tile did not sag over time. This was because material properties needed to reduce sagging also reduced the acoustic performance of the product, and the uniform material with a good absorption coefficient deflected too much over time[43].



Graph 2.6: Sound absorption coefficient of tyre fluff at different densities, at 80 mm thickness[43]

To recycle the rubber from tyres they are generally shredded into different size rubber crumbs. Using these rubber crumbs mixed with an adhesive has been widely researched[44,45,46]. Similar size rubber crumbs are mixed with an adhesive to create a granular porous absorber. It has been found that larger particles (above an average diameter of 1 mm) start to show resonant absorber properties that are highly dependent on the granulate size and thickness of the product. Graph 2.7 shows the absorption coefficient of a 90 mm thick rubber granulate product where the average granulate diameter was 1.4 mm (solid line), 4 mm (dotted line), and 6 mm (dashed line)[45]. The smaller the particle size, the less resonant behaviour is seen, with particles between 0.5 and 1 mm showing almost no resonant behaviour. However the smaller particle sizes have a lower absorption coefficient at the higher frequencies[46].



Graph 2.7: Normal absorption coefficient of 90 mm thick rubber granulate absorption product with 1.4 mm (+), 4 mm (☐), and 6 mm (o) granule size[45]

2.8 Summary

There is an extensive list of commercially available ceiling tiles that have different acoustic and non-acoustic properties to allow their use within any type of space. Due to this large variety of ceiling tiles, international standards have been developed to ensure that all absorbing products can be easily compared to each other without bias or prejudice. International standards include ASTM C423-09a and ISO 354:2003 for random incidence sound absorption measurements and ISO 10534-1:1996 for normal incidence sound absorption measurements. While the random incidence sound absorption measurement standards differ marginally, Beschel *et al*[37] found that the one-third octave band absorption coefficients do not vary significantly. However the calculation of the single number ratings can vary depending on the overall spectrum for the absorber.

The sound absorption afforded by the front face of a ceiling tile is well documented as this faces the room. This face is the only side of the ceiling tile that is measured by the suppliers and manufacturers of ceiling tiles.

Absorption within the plenum is expected to increase the TL between rooms as less reflected sound will cross the plenum. Therefore any additional absorption from the back face of the ceiling tile can be measured in order to quantify the amount of absorption and predict the additional acoustic separation provided.

Extensive research has been completed on the physical properties (both microscopic and macroscopic) of porous absorbers to produce theoretical models to predict the normal incidence sound absorption of the products without acoustic testing. A less complex model of the sound absorption, but more widely used is the Delany and Bazley empirical model, which uses the flow resistance of a product to predict the normal incidence. However, this model is shown to give less accurate results at low frequencies. Allard and Champoux developed more theoretical models, which require the determination of more parameters of a product to be able to more accurately predict the normal incidence sound absorption coefficient of the product. While these models are accurate at predicting the normal incidence sound absorption, measurements within a reverberation room are made in a diffuse, random sound field, measuring the random incidence sound absorption of a product. The statistical model developed by McGroy *et al*[21] was found to be the most accurate when predicting the random incidence sound absorption from the predicted normal incidence sound absorption.

3.0 Measurements of Sound Absorption Coefficients

3.1 Overview

The random incidence sound absorption coefficients of several different ceiling tiles and porous panel absorber products were determined using the reverberation room at the University of Canterbury. The method used to determine the absorption of the ceiling tile products are described in this chapter.

3.2 Relevant Standards

ISO 354:2003, and ASTM C423-09a describe a method for determining the random incidence sound absorption coefficients for a product. The ASTM standard was developed in North America and provides a method of determining the average sound absorption from the calculated one-third octave bands between 125 Hz and 3,150 Hz, rounded to the nearest 0.01, called the SAA. The ISO standard was developed in Europe, and uses a standardized curve fitted to the calculated octave band absorption coefficients between 250 Hz and 4,000 Hz to produce a single number weighted sound absorption rating (α_w).

A comparison of the requirements of these two standards is shown in Table 3.1. The measurements used for determining the absorption coefficients of the products in this research were in direct accordance with ISO 354:2003. The measurements undertaken were also in accordance with ASTM C423-09a with the exception of the delay to the start of measurement and the decrease in sound level. Beschel *et al* previously studied the differences between the sound absorption coefficients determined using the ISO and ASTM standards and found that there were no significant differences in results[37], as described in section 1.3.1.

Table 3.1: Comparison of the requirements of ASTM and ISO standards[37]

Property	ASTM C423	ISO 354
Minimum room volume	125 m^3, recommended ≥ 200 m^3	150 m^3, recommended ≥ 200 m^3
Maximum room volume	None given	500 m^3
Temperature and Humidity	≥ 40% RH	30 – 90 % RH, and ≥15 ^oC
Minimum sample size	5.57 m^2	10 m^2
Upper limit for sample size	No limit	12 m^2, or if room volume is greater than 200 m^3, then sample size will increase by $(V/200)^{2/3}$.
Frequency range	100 – 5000 Hz	100 – 5000 Hz
Delay to start of calculations	100 – 300 ms after signal is turned off	After 5 dB drop in sound pressure
Range of calculations	25 dB level drop	20 dB level drop
Steady state noise level during collection	≥45 dB above background noise level	≥10 dB above background level
Number of sound source positions	≥1	≥2
Placement of sample	Asymmetric; ≥0.75 m from a reflecting surface	Asymmetric; ≥0.75 m from a reflecting surface
Minimum number of microphones specified and placement	≥5 (fixed) ≥1.5 m apart, ≥0.75 m from sample surface	≥3 (fixed) ≥1.5 m apart; ≥2.0 m from sound source; ≥1.0 m from reflective surface
Minimum number of decay curves collected	50 (≥10 per microphone)	≥12
Reported values	SAA: average for (12) 1/3 octave bands from 200 – 2500 Hz; rounded to 0.01 before averaging	α_w calculation required outlined in ISO 11654-2002

As shown in Table 3.1, ISO 354:2003 requires a larger sample size, and a larger reverberation room volume than ASTM C423-09a. When measuring the decay rate in a reverberation room the ASTM standard requires the delay before the start of the reverberation time measurement as a time-based parameter, whereas the ISO test requires a sound reduction parameter before the start of the reverberation time measurement[37].

The SAA single number rating is the arithmetic average of the one-third octave band centre frequency absorption coefficients between 250 Hz to 2,500 Hz, whereas α_w is compared with a fitted reference curve, and the value at 500 Hz is the single number rating.

While the ISO standard is commonly used in New Zealand, the overall SAA value outlined in ASTM C423-09A is generally given, as it is an easily computed arithmetic average of the one-third octave bands between 250 and 2,000 Hz rather than the ISO 11654:2002 standard, which requires the calculated octave bands to be fitted to a standardised graph, as shown in Graph 1.2.

3.3 Measurement method

The sound absorption of the front face of the ceiling tile was determined in order to calculate the absorption coefficient of a ceiling tile facing into the room. This face of the ceiling tile provides absorption to the room it is located in.

Measurements were also conducted for the back face of the ceiling tiles to determine the absorption coefficient of the tile surface facing into the plenum in the CFN facility. The back face absorption was expected to reduce the sound build up within the plenum space. It was theorised that if the sound build up in the plenum were reduced, there would be a decrease in the sound transmitted between rooms sharing a common ceiling plenum. To allow this to be quantified, the absorption coefficient of the back face of the ceiling tile was determined.

Four thicknesses of porous glass fibre absorption were also tested in the reverberation room for the examination of the change in TL through the plenum sound path. 15 mm, 25 mm, 40 mm, and 100 mm glass fibre porous absorbers were tested, and the sound absorption afforded by these products was correlated to the TL though the plenum sound path in Chapter 9. The perimeter plenum absorption was also tested in the reverberation room to ensure that the product met the minimum absorption coefficients outlined in ASTM E1414-11a[47].

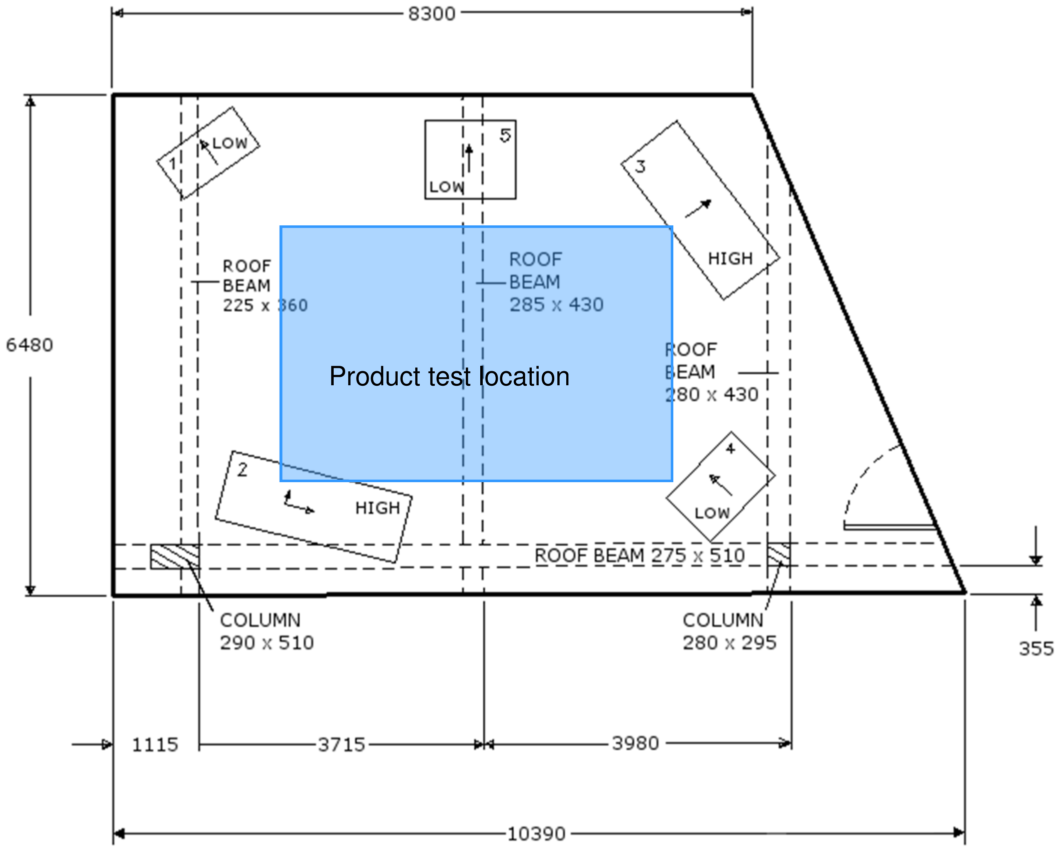
3.3.1 Reverberation

Sound from a source that is suddenly turned off continues to be heard for some time, due to the sound being reflected off walls, floors, ceilings, and other surfaces within the space. Hard dense surfaces (surfaces that have an absorption coefficient close to 0) reflect sound more readily than soft porous products that typically absorb sound (absorption coefficient close to 1). A room that has many hard reflecting surfaces slowly reduces the sound level in the room compared to a room that has porous, soft surfaces.

Reverberation time, is described as the time taken for sound produced from an interrupted source to reduce by 60 dB (T_{60}). This is found by generating a sound in a space and measuring the time it takes to reduce by 60 dB once the sound source is switched off. In practice, to measure the full 60 dB decay is difficult, and so either a 20 dB (T_{20}) or 30 dB (T_{30}) decay is measured and the T_{60} is obtained by extrapolation.

3.3.2 Reverberation room

The reverberation room at the University of Canterbury, used for this research, has a right-angled trapezoidal plan with five stationary diffusers and three structural beams. No two room dimensions are equal or in the ratio of small whole numbers. The volume of the room is 216.8 m^2. A sufficiently diffuse sound field is established by the inclusion of the diffusing panels that are constructed of galvanised steel faced medium density fibreboard (MDF) with the sides of the MDF painted to increase reflectivity. Each diffusing panel has a one-sided area of 2.88 m^2 and is suspended with a random orientation. The diffusing panels are large enough to disrupt the low frequency sound waves. The total two-sided area of the diffusing elements is 0.13% of the total boundary surface area of the room. Previous tests carried out in the room have established that diffusivity of the room is acceptable[48]. The total surface area of the room boundaries and diffusing elements is 305.06 m^2. The reverberation room layout including placement area for absorption samples is shown in Figure 3.1 below.

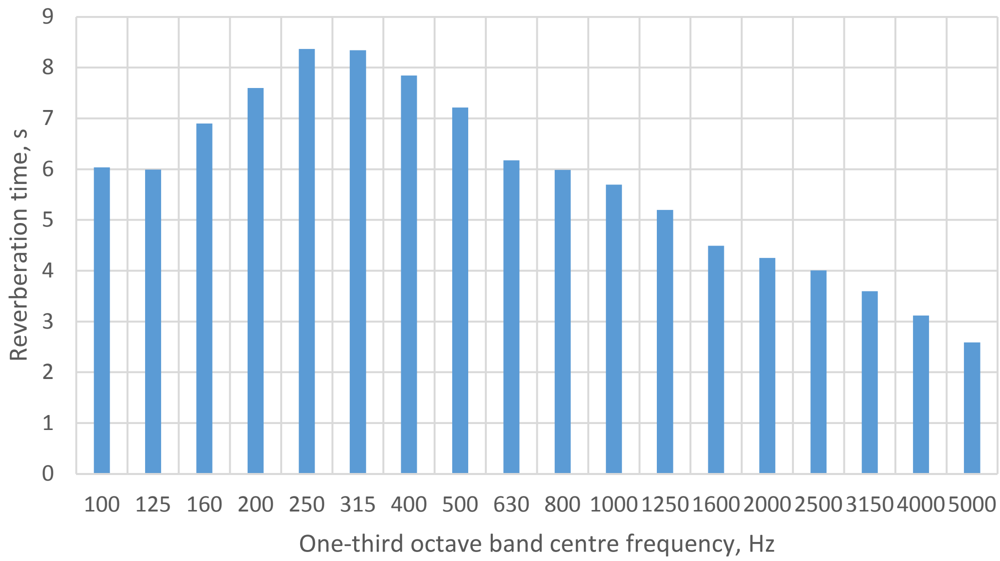


Notes:
1. Room Volume 216.8 m^3
2. Room Surface Area 270.5 m^2
3. Total Diffuser Area 34.56 m^2
4. Arrows on Diffusers Point Downwards
5. "High / Low" Indicates Height Location in Room
6. All dimensions in millimetres

Figure 3.1: Diagram of the reverberation room at the University of Canterbury

The reverberation time within the empty reverberation room at the University of Canterbury at 17 °C with a relative humidity of 60 % in one-third octave bands is shown in Graph 3.1 below.

It was assumed, from previous work, that the sound field within the reverberation room was sufficiently diffuse for this work[48].



Graph 3.1: Reverberation time of the reverberation room at the University of Canterbury

3.3.4 Product specimens

The absorption coefficients of five different ceiling tile products were determined. All the ceiling tiles were square edged (had no recessed edges), and were each sized approximately 1195 x 595 mm (2.5 mm clearance each side to fit into a 1200 mm by 600 mm suspended ceiling grid). Four of the ceiling tile products were made from mineral fibre (AMF Thermatex Silence, Armstrong Ultima, Daiken New NDF, and USG Mars), with one composite tile consisting of a porous glass fibre front with a plasterboard backing (T&R Interior Systems CMax Combo 35).

The front of the glass-fibre ceiling tile of the T&R Interior Systems CMax Combo (which is typical of all porous absorbers) is made from thin fibres bound together into a mat-like structure. The fibres are made by heating multiple elements together (typically glass, sand, soda ash and limestone) in a large furnace to between 1200 °C and 1600 °C. This molten mixture then falls into a spinning chamber where centripetal forces push the molten liquid to the outside of the chamber, which is perforated. Due to this centripetal force, the molten liquid is forced though the perforations, creating fine glass fibres, which are cooled on contact with compressed air that is blown though the fibres. The glass fibres drop from the spinning chamber, through a spray of a polymer binder and onto a flat surface forming layered sheets. These sheets are then heated to set the binder and are then cut into appropriate sizes for use.

A similar procedure can be used for making mineral fibre ceiling tiles. However, before the binder is set the sheets are compressed, which increases the fibre density within the product. The binder is then set, the resultant sheets are more rigid and dense compared to glass fibre ceiling tiles. Typically a facing is applied to the front face, before the sheet is cut into the required sizes.

Daiken New NDF was the thinnest mineral fibre ceiling tile used in this research, with a thickness of 12 mm. The USG Mars and Armstrong Ultima ceiling tiles both had a thickness of 19 mm, with the AMF Thermatex Silence ceiling tile being the thickest mineral fibre ceiling tile at 42 mm. The T&R CMax Combo 35 ceiling tile had a front porous glass-fibre thickness of 25 mm adhered to a 10 mm plaster backing.

The USG Mars, AMF Thermatex Silence, Armstrong Ultima, and CMax Combo ceiling tiles have a separate tissue facing adhered to the mineral fibre or porous glass fibre front. The facing of the Daiken New NDF is painted directly to the mineral fibre, with penetrations to allow sound to penetrate the paint.

The five ceiling tile specimens were tested in two configurations, as described in ISO 354:2003:

- Mount Type-A, which is directly laid on the floor, and
- Mount Type E-400, with a 400 mm cavity behind the facing of the ceiling tile.

ISO 354:2003 gives multiple distances that the cavity behind the facing of the ceiling tile can be, however 400 mm was chosen for this research as it is the largest cavity that ISO 354:2003 specifies[22] and is also nearest to the depth created by the plenum within the CFN facility (described later in Chapter 6).

The sound absorption of the front and back face of the ceiling tile in mount Type-A was determined. Only the sound absorption on the front face was determined in mount type E400.

The absorption coefficients of porous absorbers were also determined both for the perimeter plenum absorption to ensure compliance with ASTM E1414-11a[47], and for the different thicknesses of absorption added to the plenum to determine what effect the sound absorption played in the TL. All porous absorber products were tested in mount Type-A.

The area of ceiling tiles that were tested was three ceiling tiles long, by five ceiling tiles wide (1200 mm x 600 mm), total dimensions of 3600 mm long by 3000 mm long, giving an area of 10.8 m^2. The porous absorber products ranged in sizes, and the areas tested were between 10.6 m^2

and 11.85 m^2. The absorption area of all products was surrounded by steel angle sections, such that the edge effect (additional absorption due to the exposed edges of the products) was minimised as far as practicable, in accordance with ISO 354:2003.

3.4 Measurement procedure

Measurements and calculations to determine the absorption coefficients of the sample products were completed in accordance with ISO 354:2003, and are described below. Sound absorption coefficients determined by reverberation room testing represent the ratio of absorbed sound to incident sound energy over all angles of incidence (random incidence sound absorption).

The environmental conditions in the reverberation room were first checked within the reverberation room to ensure that the humidity was above 30 % and below 90 % (ideally above 60 %), and the temperature was above 15 ^{o}C. These two parameters, as well as the barometric pressure, were recorded. Six microphones were laid out in the positions shown in Figure 2.2 below, such that they were a minimum of 1.5 metres from each other, a minimum of 2.0 metres from the sound source, and at least 1.0 metre from a reflecting surface. The loudspeaker was set up in position 1 as shown in Figure 3.2.

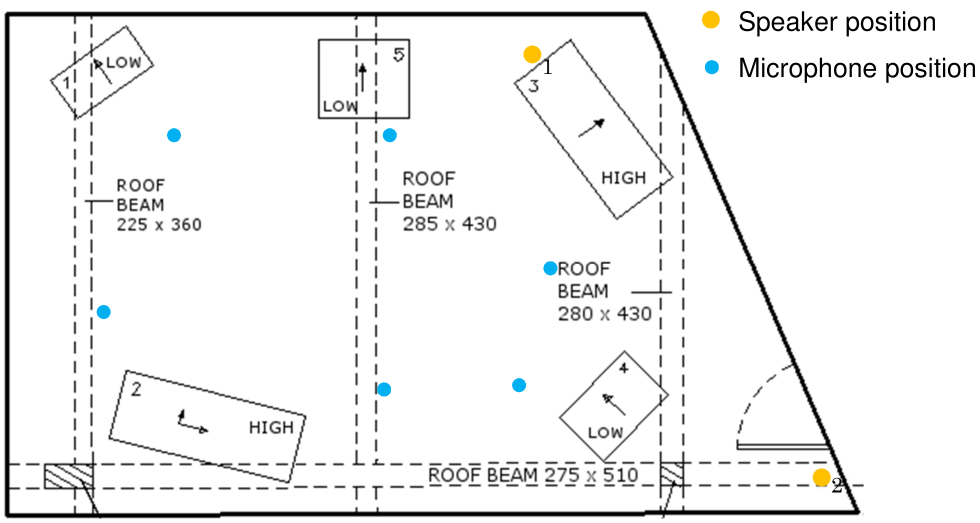


Figure 3.2: Microphone and speaker positions within the reverberation room

The empty room reverberation time was first measured. The loudspeaker in position 1 (furthest away from the door, subscript 1) played a broad-band pink noise for seven seconds and then was shut off. The time taken for the sound to decrease by 20 dB, (T_{20}) at all microphone positions was measured using a Bruel and Kjær PULSE Multi Analyser System. The T_{60} values were then extrapolated from the T_{20} measured. The T_{20} was measured for the first speaker position a total of three times, using the same technique, and the average T_{60} for each microphone position was calculated.

The speaker position was then moved to position 2 (closest to the entry door, subscript 2). The above method was repeated three additional times to determine the T_{20}, from which to extrapolate the T_{60}. The average T_{60} of the three measurements at speaker position 2 was calculated for each microphone position. An overall average T_{60}, calculated from the averages of speaker 1 and speaker 2, position was then calculated for each microphone position.

The environmental conditions were then recorded, to ensure that there had been no significant change between the start and end of the measurements. The speaker was then moved back to the first speaker position.

The absorption product for testing was then installed in the reverberation room such that it had a total surface area between 10 m^2 and 12 m^2, and the ratio of length to width was between 1:0.7 and 1:1. The product was no less than 1.0 metre from any wall or reflecting surface. Steel sections were placed around the perimeter of the test product, as recommended in ISO 354:2003. The environmental conditions were then noted and three reverberation time measurements were completed as described above. Once the three measurements were completed at both speaker positions, the environmental conditions were then measured again to ensure that there had been no significant change over the period of testing.

The reverberation time measured using the reverberation room method were then used to calculate the absorption coefficients as described in section 3.4.1 below.

3.4.1 Calculation of absorption coefficients

To calculate the absorption coefficients from measured reverberation times, the following calculation method, as described in ISO 354:2003 was used.

Three measurements are taken at six microphone positions for each of the two loudspeaker positions. The reverberation times measured at the same microphone position were arithmetically averaged for each speaker position for each three tests, to obtain the average T_{60}. The average at each loudspeaker position are further arithmetically averaged over both loudspeaker positions to determine the overall average reverberation time for the empty and room with the test specimen.

Next, the equivalent sound absorption area of the empty reverberation room (A_1) was calculated, which was completed by dividing the volume of the room by the speed of sound (taking into consideration the environmental conditions) and the average reverberation time within the empty reverberation room, using Equation 3.1.

$$A_1 = \frac{55.3V}{cT_1} - 4Vm_1 \qquad \text{Equation 3.1}$$

Where V is the volume of the room in m^3, c is the speed of sound in air in ms^{-1}, T_1 is the reverberation time in seconds of the empty reverberation room, and m_1 is the power attenuation coefficient, which is calculated using Equation 2.2.

$$m = \frac{\alpha}{10\lg(e)} \qquad \text{Equation 3.2}$$

Where α is the absorption coefficient for the specific frequency according to the atmospheric conditions within the reverberation room (found using Equation 5 in ISO 9613-1:1993).

Next, the equivalent sound absorption area of the reverberation room with the absorption product located in (A_2) was calculated. This was done using Equation 2.3:

$$A_2 = \frac{55.3V}{cT_2} - 4Vm_2 \qquad \text{Equation 3.3}$$

Where V and c are as described above, T_2 is the reverberation time of the reverberation room with the product added, and m_2 is the power attenuation coefficient which was calculated using Equation 3.2.

The sound absorption area of the product (A_T) in m^2 was calculated using Equation 3.4:

$$A_T = A_2 - A_1 = 55.3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1) \qquad \text{Equation 3.4}$$

Where c_1 was the speed of sound in the reverberation room with no product added, c_2 was the speed of sound in the reverberation room with the absorption product added. A_1, A_2, V, T_1, T_2, m_1, and m_2 have been defined above.

From these calculations the random incidence sound absorption of the product can be calculated at each frequency using the following expression:

$$\alpha_s = \frac{A_T}{S} \qquad \text{Equation 3.5}$$

Where A_T was the equivalent sound absorption area, calculated in Equation 3.4 above, and S was the area of the product being tested in square metres.

3.5 Summary

To determine the absorption coefficient of sound absorbing products, two standards are generally followed, these are ISO 354:2003, and ASTM C423-09a. The measurements undertaken for the current research employ the interrupted noise method as outlined in ISO 354:2003, employing the reverberation room at the University of Canterbury.

The absorption coefficients of five different ceiling tiles and five thicknesses of porous absorber products were determined using the method described in ISO 354:2003. Four of the five ceiling tile products were mineral fibre ceiling tiles, with differing material properties, made by different manufacturers. The fifth ceiling tile was a composite ceiling tile that consisted of a 25 mm porous front material, with a 10 mm thick backing of plasterboard. Porous bulk absorbers were also determined to ensure that the perimeter plenum absorption met the requirements in ASTM E1414-11a, and the sound absorption in the plenum could be correlated to the change in TL through the plenum sound path.

4.0 Sound Absorption Results

4.1 Overview

This chapter presents the results of the sound absorption measurements of various ceiling tiles and porous absorbers. The sound absorption measurements were made on the front face of the ceiling tile with and without a cavity behind the ceiling tiles, as well as the back of the ceiling tile without a cavity. Porous absorbers were only tested on one side, directly laid on the floor of the reverberation room.

4.2 Sound absorption measurements of ceiling tiles

The sound absorption of the ceiling tile products are presented below. The results are separated into three sections:

- Front face of ceiling tile facing the sound field,
- Back face of ceiling tile facing the sound field, and
- Front face of ceiling tile facing the sound field with a 400 mm cavity behind the facing.

The sound absorption of five different ceiling tile specimens was measured with the front face and then the back face facing the sound field. Three of these ceiling tile specimens (T&R CMax Combo 35, Daiken New NDF, and USG Mars were tested in mount Type E-400, as described in ISO 354:2003.

The complete set of results are tabulated in Appendix A.X.

4.2.1 Sound absorption of the front face

The five ceiling tile specimens were first tested in mount Type-A, described in ISO 354:2003, with perimeter steel angle laid hard against the perimeter of each area of the ceiling tile product. The ceiling tile products in this configuration are shown in Figure 4.1.

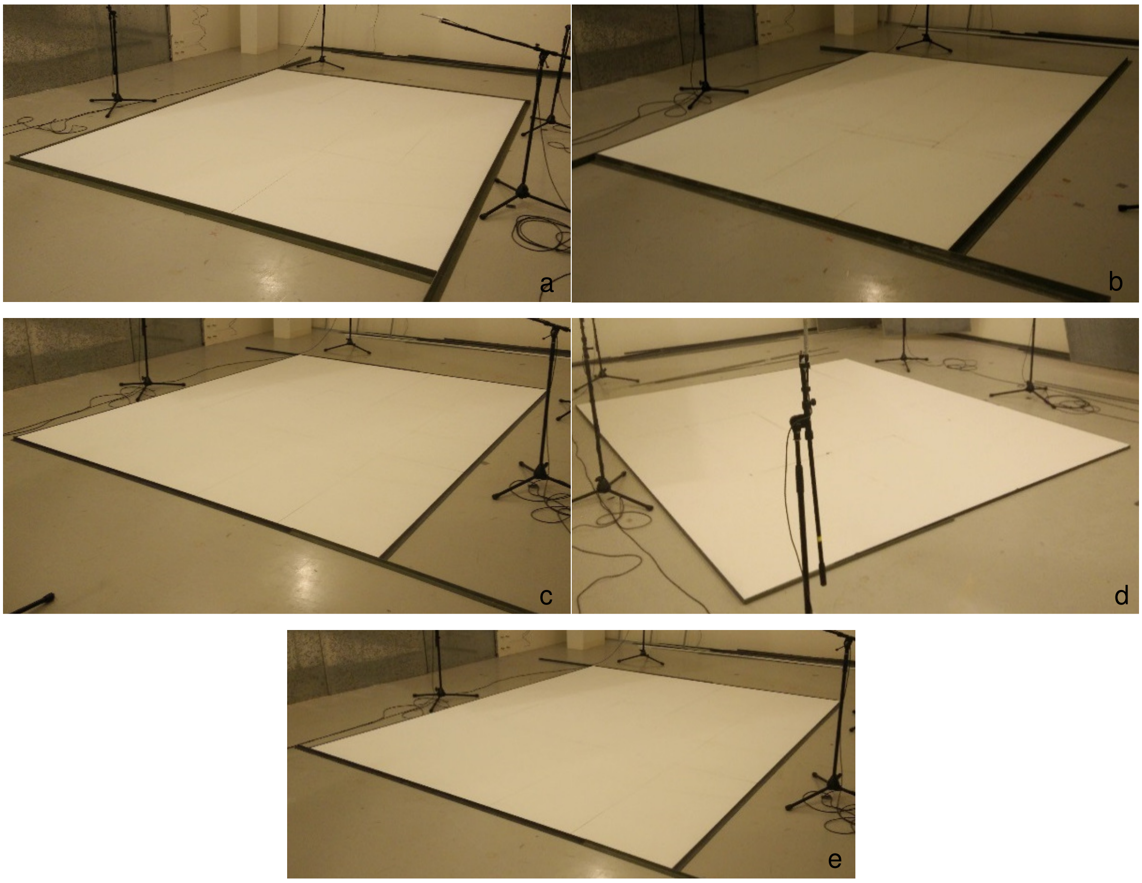
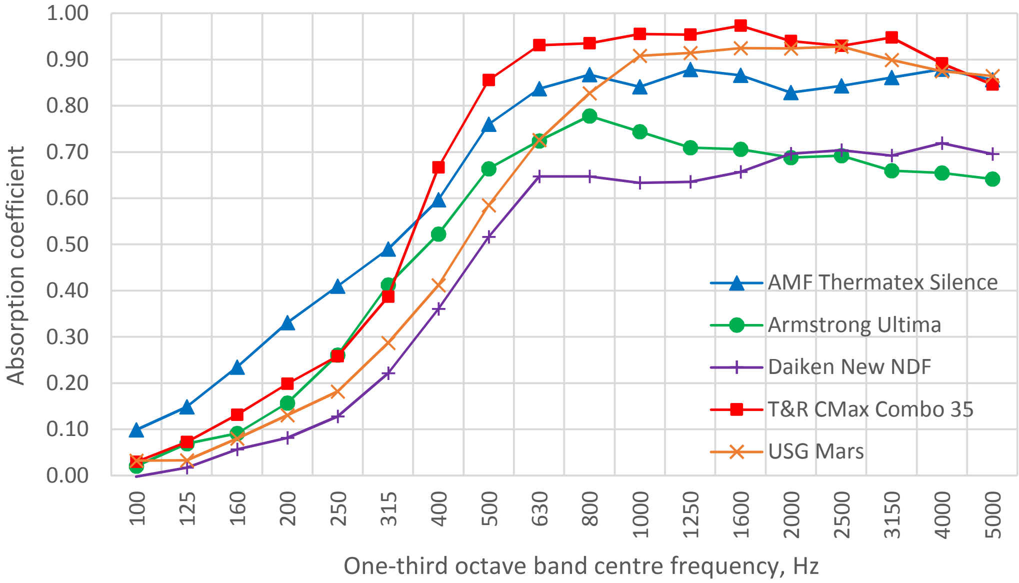


Figure 4.1: Ceiling tiles installed within reverberation room with front facing the sound field. a) T&R CMax Combo 35, b) AMF Thermatex Silence, c) Daiken New NDF, d) Armstrong Ultima, and e) USG Mars

The sound absorption results from the tests are shown in Graph 4.1. The sound absorption results are largely as expected. The T&R Interior Systems CMax Combo 35 had the highest absorption coefficient, probably due to the more porous 25 mm glass fibre facing. The Daiken New NDF ceiling tile has the lowest measured sound absorption due to this tile being the thinnest used in this research.

The majority of these products have been previously been tested and when the results are corrected due to different mounting conditions, the results measured by the author agree well with those currently provided on the product datasheets.



Graph 4.1: Absorption coefficients of the front face of the ceiling tiles placed directly on the floor of the reverberation room

The general trend of each of the absorption coefficient curves is typical of a porous absorber, having a relatively low absorption at the lower frequencies, with the absorption coefficient of the product rising with increasing frequency, and plateauing at a specific absorption coefficient, determined by the material properties.

The USG Mars (marked as an 'X' in Graph 4.1), and Armstrong Ultima (marked as a '●' in Graph 4.1) are the same thickness, and were expected to have a similar sound absorption. However, the Armstrong Ultima has a higher absorption coefficient below 630 Hz whereas the USG Mars has higher absorption coefficient above 630 Hz. This is probably due to the differences in the mineral fibre substrate (structure and layout of the fibres).

The maximum sound absorption of the AMF Thermatex Silence (marked as a '▲' in Graph 4.1) is approximately 0.85, which was lower than expected. The AMF Thermatex Silence is constructed of two different mineral fibre layers that are bonded together. The backing mineral fibre is denser and is glue bonded to the front that is more porous. The effective absorption of the ceiling tile is therefore expected to be limited to the 30 mm front mineral fibre rather than the full 42 mm thickness of the ceiling tile.

4.2.2 Back face ceiling tile measurements laid on the floor

The sound absorption afforded by the back face of the five ceiling tile products were measured in the reverberation room. The ceiling tile products were laid directly on the floor of the reverberation room (mount Type-A), with the tissue face, facing the floor of the reverberation room. These measurements were to determine the absorption afforded by the ceiling tile that faces the plenum.

Figure 4.2 below shows the ceiling tile products installed within the reverberation room, with the back of the ceiling tile facing the sound field, with perimeter steels surrounding the specimen, described in ISO 354:2003.

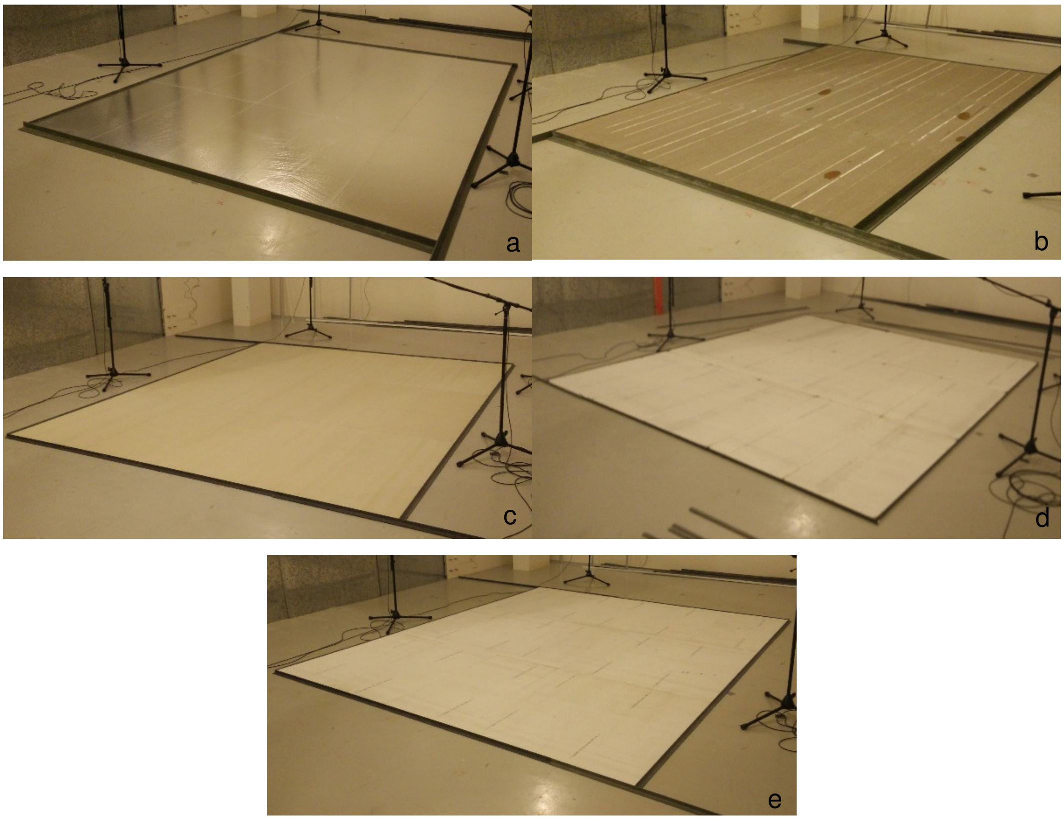
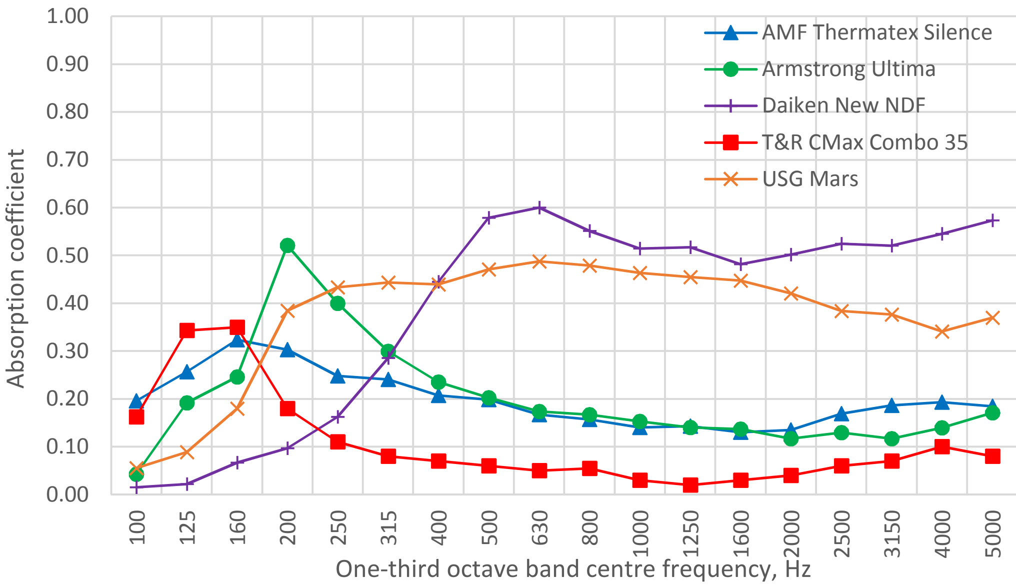


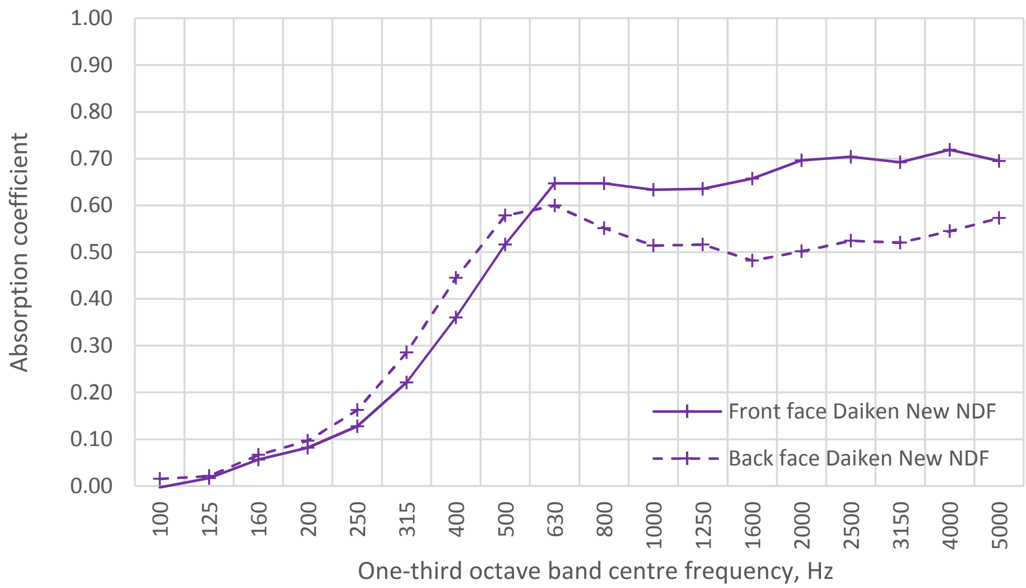
Figure 4.2: Ceiling tiles installed within reverberation room with the back facing the sound field. a) T&R CMax Combo 35, b) AMF Thermatex Silence, c) Daiken New NDF, d) Armstrong Ultima, and e) USG Mars



Graph 4.2: Absorption coefficients of the back face of the ceiling tiles placed directly on the floor of the reverberation room

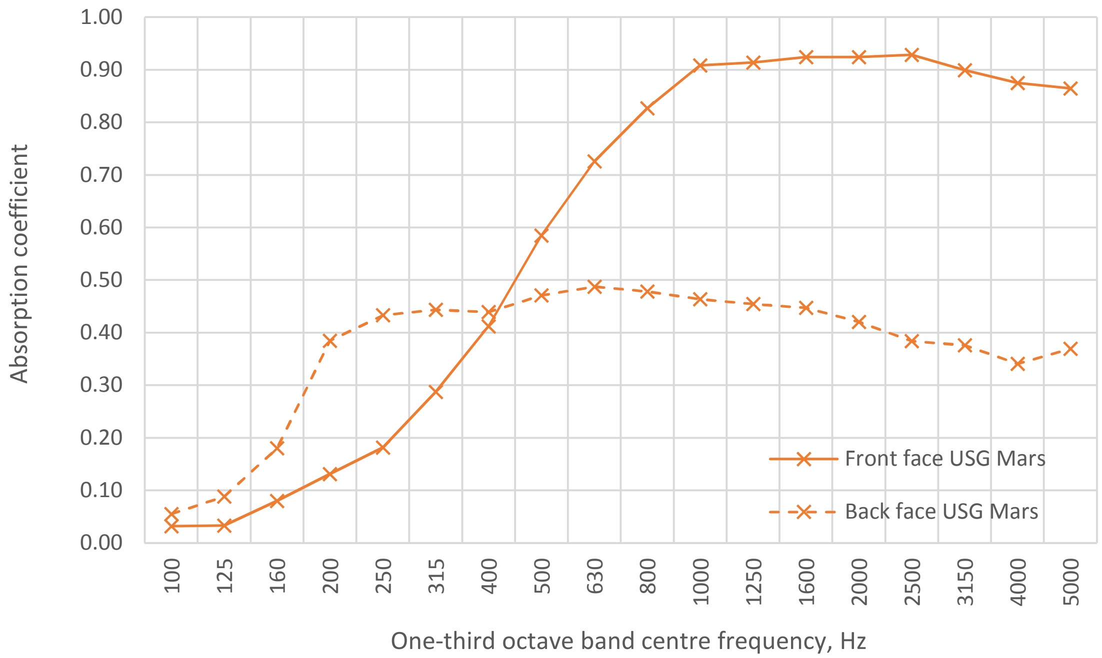
As expected, the T&R Interior Systems CMax Combo 35 ceiling tile (marked as a '•' in in Graph 4.2) performed poorly, as this was essentially a plasterboard layer over an absorption filled cavity. As plasterboard is acoustically reflective, the absorption coefficient, especially at mid-to-high frequencies is poor (below 0.1). The absorption coefficient curve is typical for a plasterboard product, providing more absorption at low frequencies, as 6he plasterboard vibrates and dissipates the sound energy, while at mid-to-high frequencies, the sound is largely reflected.

The back face of the Daiken New NDF ceiling tiles (marked as a '+' in Graph 4.2) showed that it performed almost as well as the front face of the ceiling tile, which may indicate there is little coating on the back of the ceiling tile. Graph 4.3 below shows the comparison between the front face (solid line), and back face (dashed line) of the Daiken New NDF ceiling tile. The overall absorption coefficient curve was that of a typical porous absorber. Between 100 Hz and 500 Hz, the back face of the Daiken New NDF ceiling tile performed better than the front face.



Graph 4.3: Comparison of the front face (solid) and back face (dashed) absorption coefficients of the Daiken New NDF ceiling tiles

The absorption coefficient curve of the back face of the USG Mars ceiling tile (orange line in Graph 4.2) is typical of a porous absorber, however the overall absorption coefficient measured was lower than that of the front face. It was surprising to see that the absorption coefficient curve increased at a higher rate compared to the front face of the ceiling tile. This increase was a maximum at 250 Hz, where the back face exhibited a 0.25 increase in absorption coefficient than the front face. 250 Hz was the peak of the absorption coefficient curve on the back face, and the absorption coefficient curve plateaued at approximately an absorption coefficient of 0.4. The front face, while increasing at a steadier rate, increased well past that provided by the back face, peaking at 0.9 at 1,000 Hz, and plateauing at the same absorption coefficient. The difference seen between the front face and back face of the USG Mars ceiling tile was attributed to the sealant casing the tile to act as a resonant absorber, but also be acoustically transparent enough for the sound to be absorbed within the mineral fibre. However a more detailed analysis into the effect of sealant and additions to the mineral fibre and front facing tissue would need to be undertaken to determine if this was an appropriate conclusion. The front face (solid line) and back face (dashed line) absorption coefficients for the USG Mars are shown in Graph 4.4.



Graph 4.4: Comparison of the front face (solid) and back face (dashed) absorption coefficients of the USG Mars ceiling tiles

Due to the large peak of the absorption coefficient graph at 200 Hz, it is expected that the additives / glue on the back of the Armstrong Ultima ceiling tile is causing the tile to act as a resonant absorber.

The resonant absorber phenomena seen on the back face of the Armstrong Ultima ceiling tile is seen also on the rear face of the AMF Thermatex Silence ceiling tile. This additive layer was expected to be thicker than the layer on the Armstrong Ultima ceiling tile as the peak is at a lower frequency. The low absorption performance of the AMF Thermatex Silence ceiling tile could also be put down to the denser backing mineral fibre layer that is designed for reducing the sound passing through it rather than absorption.

Overall, the absorption coefficient results of the back face were lower than the results on the front face of the ceiling tile products. It is expected that this is from the additives (including sealers) on the back face and sides of the ceiling tile that make the ceiling tile more durable during installation and throughout its lifecycle.

4.2.3 Front face ceiling tile measurements with a cavity

Tests of three ceiling tile products were also measured with a 400 mm cavity behind the tile, described as mount Type E-400 in ISO 354:2003. These tests were undertaken to determine the absorption provided by a suspended ceiling when a plenum was present behind it, which is standard practice in commercial office and educational spaces usually to hide services.

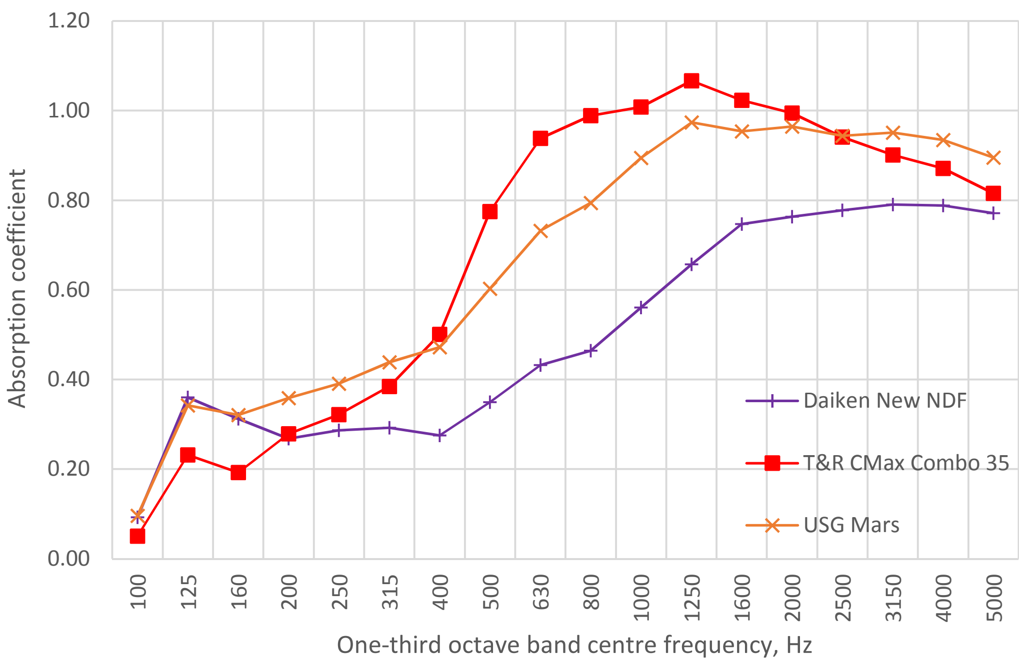
A medium density fibreboard (MDF) varnished frame was made up to fit the 15 tested ceiling tiles, that a suspended ceiling grid was installed in, which could be varied in height depending on the height of the ceiling tile product to be measured. This allowed the ceiling tiles to be measured with an air cavity behind them. Preliminary tests were undertaken without and with just the frame and the suspended ceiling grid installed in the reverberation room. It was determined the frame had absorption coefficients of less than 0.1 in all relevant one-third octave bands. The frame was sealed to the floor of the reverberation room to attenuate any sound passing under the frame. The box with the suspended grid is shown in Figure 4.3 below.

Figure 4.3: Box installed in the reverberation to measure the absorption coefficients of ceiling tiles over a 400 mm cavity

The ceiling tiles were installed with the front tissue face of the ceiling tile product facing the sound field, with the face installed 400 mm above the floor of the reverberation room (mount Type E-400).

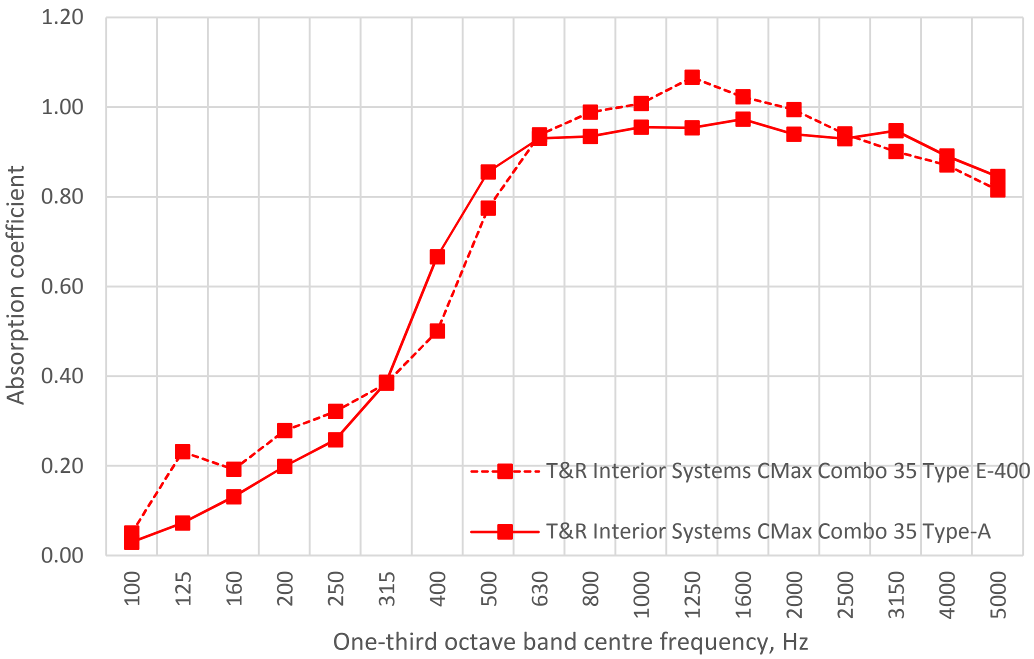
Figure 4.4 below shows the three ceiling tile products installed, in the Type E-400 frame. The perimeter of the ceiling tiles are covered by a combination of the MDF frame and perimeter of the suspended ceiling grid to minimise sound absorbed around the edges.

Figure 4.4: Ceiling tiles installed within reverberation room in mount Type E-400. a) T&R CMax Combo 35, b) Daiken New NDF, and c) USG Mars

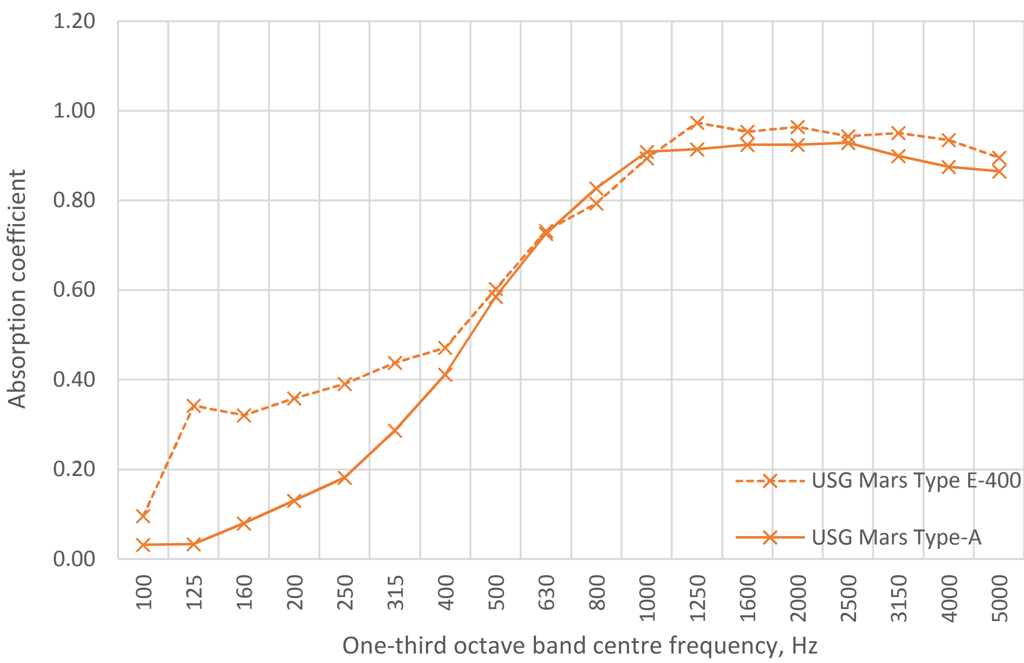


Graph 4.5: Absorption coefficients of three ceiling tile products installed in mount Type E-400

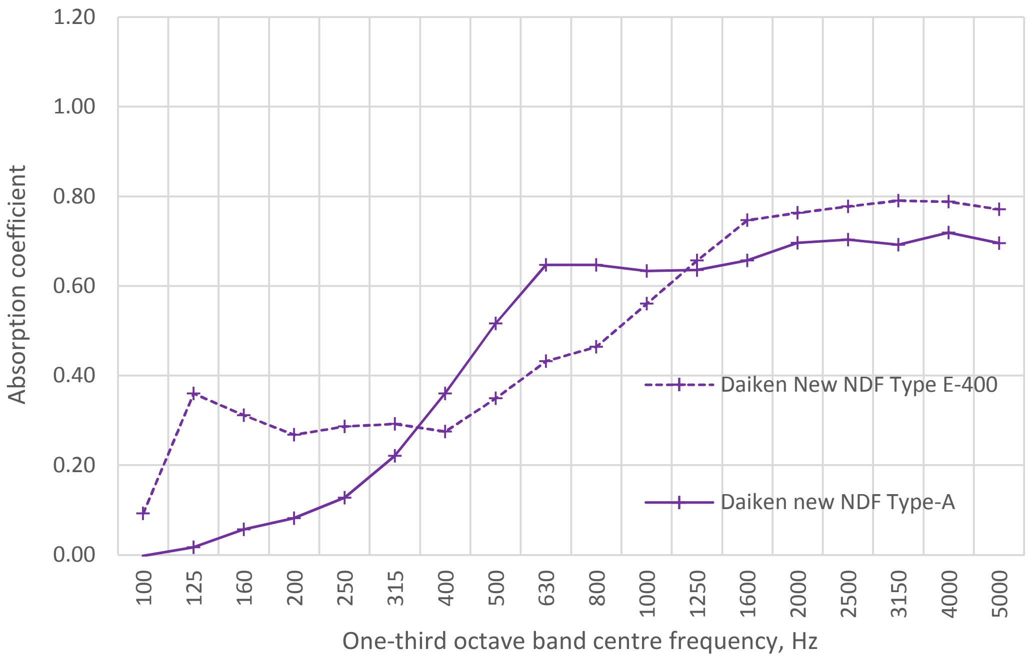
With the 400 mm cavity behind the ceiling tiles, the results showed that sound absorption below 315 Hz increased, with moderate overall increase at mid-to-high frequencies, as is expected when a porous absorber is mounted over an air cavity. There is little change between the mount Type-A and mount type E-400 of the T&R CMax Combo 35 ceiling tile due to the plasterboard reflecting the sound before it can pass through the ceiling tile into the plenum. Graph 4.6 to 4.8 plots the absorption coefficients of the direct mounted ceiling tile measurements (mount Type-A), as a solid line, and over a 400 mm air cavity (mount Type E-400), as a dashed line.



Graph 4.6: Absorption coefficients of T&R Interior Systems CMax Combo 35 ceiling tile installed in mount Type E-400 (dashed line) and mount Type-A (solid line)



Graph 4.7: Absorption coefficients of USG Mars ceiling tile installed in mount Type E-400 (dashed line) and mount Type-A (solid line)



Graph 4.8: Absorption coefficients of Daiken New NDF ceiling tile installed in mount Type E-400 (dashed line) and mount Type-A (solid line)

In all three samples measured in mount Type E-400, there was an increase in absorption at 125 Hz over that measured when laid directly on the floor, and compared to the frequencies around it. This may be from the ceiling tile acting as a membrane absorber over a cavity, as it is limited to one discrete frequency.

It is unknown why the Daiken new NDF ceiling tile performs worse with a cavity though the mid frequency bands (315 Hz to 1,250 Hz) compared to when it is mounted using mount Type-A. This ceiling tile showed the largest amount of absorption on the rear surface of the ceiling tile, so it was expected that the absorption coefficient when mounted in a Type E-400 mount would increase the greatest overall compared to the other ceiling tile products tested. The low frequency absorption is increased as expected when a ceiling tile is over a cavity.

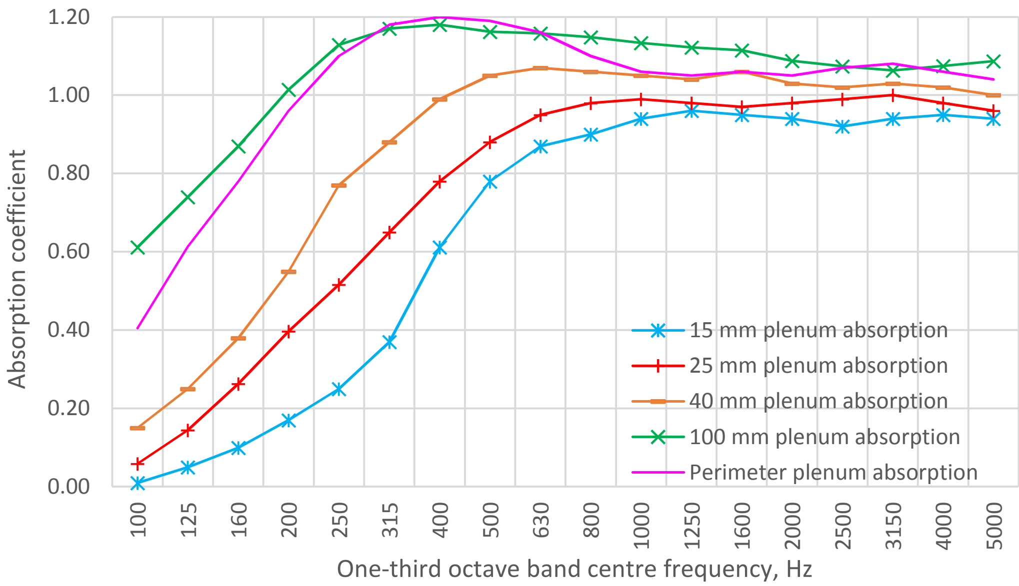
The USG Mars ceiling tile acts as expected by a porous absorber over a cavity, with a large increase in absorption at low frequencies due to the presence of the cavity. The absorption coefficient curve over a 400 mm cavity merges with the absorption coefficient curve measured without a cavity at the mid-to-high frequencies. At these mid-to-high frequencies, the absorption coefficients are comparable with the Type E-400 mount showing a small increase due to some absorption in the cavity space.

Overall these tests confirm that the absorption of a product when measured with a cavity behind, increases at low frequencies, and shows similar absorption curves at mid-to-high frequencies. When a solid backing is adhered to the back of a porous absorber, and it is tested over a cavity, the increase at the lower frequencies is less apparent.

4.3 Porous absorber results

The sound absorption of five different thicknesses of porous absorbers were determined to correlate the TL of the plenum sound path to absorption in the plenum, and to ensure the perimeter plenum absorption complies with the requirements of ASTM E1414-11a. The thicknesses of the absorption that were added to the plenum were 15 mm, 25 mm, 40 mm, and 100 mm. The perimeter plenum absorption had a thickness of 90 mm.

The density of the plenum absorption products were all 100 kg/m³ (surface density of 1.5 kg/m² for 15 mm, 2.5 kg/m² for 25 mm, 4.0 kg/m² for 40 mm, and 10.0 kg/m² for 100 mm), with the perimeter plenum absorption being 15 kg/m³ (surface density of 1.3 kg/m²). All porous absorber products were determined in mount Type–A. The results of the absorption coefficients of the porous absorbers in mount Type-A, are shown in Graph 4.7 below and tabulated in Appendix A.X.



Graph 4.9: Absorption coefficients of four different porous absorber products and the perimeter plenum absorption determined in the reverberation room at University of Canterbury

The sound absorption results from the porous absorbers show that as the thickness of the product increases, the absorption coefficient increases, with the largest increase seen at the lowest frequencies. As the thickness increases, the absorption coefficient increases, and the peak of the absorption coefficient curve shifts to the lower frequencies. This was expected, as when the thickness increases, the product is able to absorb more of the longer wavelength, low frequency sounds.

The thicker products show a higher sound absorption at higher frequencies, however the difference between the products, is much less when compared to the lower frequencies. The 40 mm, 90 mm, and 100 mm products exhibit similar sound absorption above 1,000 Hz.

4.6 Summary

The sound absorption of a series of ceiling tiles has been measured. It has been shown that the back face of a ceiling tile does not provide the same amount of absorption as the front face of a ceiling tile. This was expected, due to the additives to the back face and mineral fibre itself to increase the longevity of the ceiling tile.

The sound absorption increases at lower frequencies when a ceiling tile is tested over a cavity, as would normally be installed in practice (suspended from the roof / floor above, creating a plenum). The results showed little change to the mid and high frequencies when the ceiling tiles are tested over a cavity. When a product that has a hard backing is tested over a cavity, the absorption coefficient curve does not shift much, due to the hard backing reflecting the sound before the sound penetrates the cavity.

5.0 Background and Literature Review –Transmission Loss

5.1 Overview

The acoustic performance of a suspended ceiling system is typically described by two parameters. The first is the absorption coefficient, which relates to how much of the sound is absorbed (turned into heat). The second parameter, discussed further in this and subsequent chapters, is the ceiling attenuation class (CAC), which describes the reduction of the sound when transferred from one room into a ceiling plenum, then from the ceiling plenum into an adjacent room though the suspended ceiling system (called the plenum sound path). This chapter focuses on the transmission of sound through a suspended ceiling via the plenum sound path. Past analysis of the absorption of products is reviewed in Chapter 1.

This Chapter provides some background into transmission loss, the measurement methodology, and single number weightings. This chapter concludes with a literature review of previous work completed on ceiling tiles and suspended ceiling systems. This research is primarily based on ceiling tiles and the associated suspended ceiling grid (referred to as a suspended ceiling system), however single panel partitions are also reviewed as a suspended plasterboard or plywood ceiling are sometimes employed, to reduce leakage through the suspended ceiling. This section provides a basis for the experimental work on the transmission loss of a suspended ceiling, which is presented in the following chapters.

5.2 Transmission loss

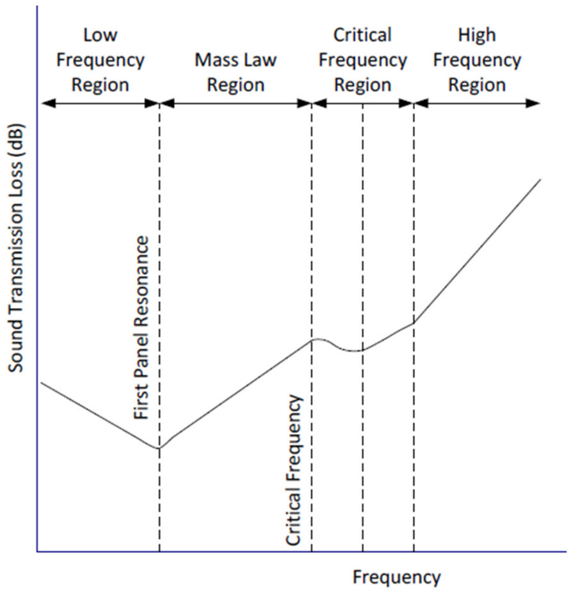
Sound transmission loss (TL) is the measure of the sound attenuation provided by a partition dividing two spaces, and is sometimes referred to as the sound reduction index. When an incident sound wave disturbs a partition, some of the sound wave is reflected back into the space, some of it is absorbed, and some is transmitted into the surrounding partition structure.

The sound reduction index (τ) is described in ISO 10140-2:2010[49] as the logarithmic ratio of the sound power (W_{inc}) that is incident on the partition to the sound power radiated by the partition on the opposite site (W_{rad}), expressed by the following equation:

$$\tau = 10\log_{10}\left(\frac{W_{inc}}{W_{rad}}\right) \qquad \text{Equation 5.1}$$

5.2.1 Transmission loss of a single panel

The TL of a single homogenous panel (such as a single panel of plasterboard, or a single glazed window) can be separated into four different frequency regions, as shown in Graph 5.1[14, 50]. The first region is at low frequencies, and is controlled primarily by the product's stiffness; which ends at the first resonance of the panel. In this region, the TL of the panel decreases towards the first panel resonance and is a minimum at the first resonance frequency of the panel. The second region lies between the first panel resonance and the critical frequency region, typically called the mass law region, as the primary material property controlling the TL of the panel is its mass[50]. The TL increases through this region at approximately 6 dB per octave. The third region is the critical frequency transition region, which sees a decreases in TL as the incident sound wave is equal to the bending wavelength of the panel. This causes the panel to resonate which transmits sound more readily between the adjacent spaces, called the coincidence 'dip'[50]. The fourth region is in the high frequencies, above the critical frequency, which is strongly influenced by the damping in the system, and shows an increase of approximately 9 dB per octave.



Graph 5.1: Typical sound transmission loss curve for a single panel system

5.2.2 Transmission loss of the plenum sound path

The TL through a single panel has been studied extensively, with a great understanding on how sound is transmitted from one side to the other. While the sound path through a suspended ceiling can be simplified to that through a single panel structure, the transmission of sound through the plenum sound path is more complex. Factors which include the TL of the suspended ceiling system (including leaks between the suspended ceiling grid and ceiling tile), absorption within the plenum, and sound propagation through the plenum have to be considered.

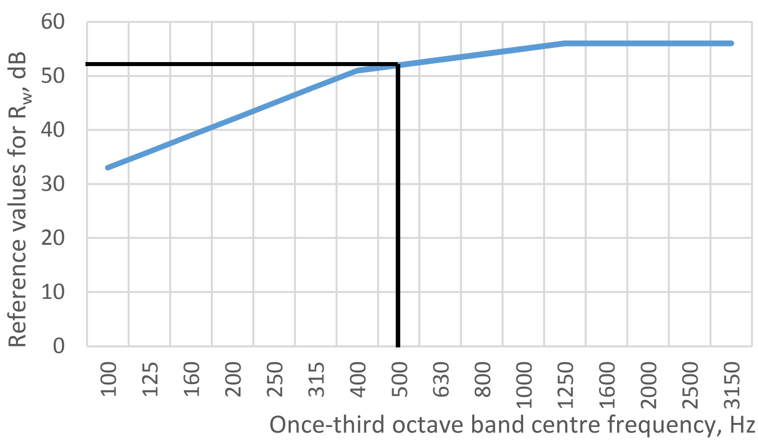
5.3 Acoustic rating of products

Single number acoustic ratings are given to a system to facilitate a quick comparison between products. The single number ratings are defined in ISO 717-1 *Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation*[51] (weighted sound reduction index (R_w)), and ASTM E413-10 *Classification for Rating Sound Insulation*[52] (sound transmission class (STC)).

For sound transmitted though the plenum, this is given a different single number rating. The single number rating for the plenum sound path reduction is defined in ISO 717-1 (weighted suspended-ceiling normalised level difference ($D_{n,c,w}$)), and ASTM C413-10 (ceiling attenuation class (CAC)).

5.3.1 Weighted sound reduction index rating

The weighted sound reduction index, R_w, is calculated by fitting the TL results, to a standardised reference curve, shown in Graph 5.2. The standardised reference curve is moved towards the measured TL at 1 dB increments until the sum of the unfavourable deviations is as large as possible, but not over 32 dB. Once this has been achieved, the value given at 500 Hz is the weighted sound reduction index. Unfavourable deviations are points that lie below the reference curve.



Graph 5.2: Reference curve for airborne sound weighted sound reduction rating calculation[51]

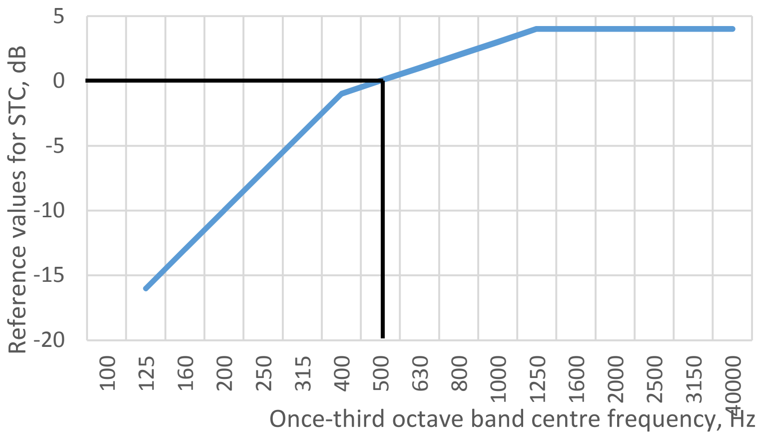
5.3.2 Sound transmission class rating

The sound transmission class rating, STC, is calculated in a similar way to the R_w rating in that it is fitted to a standardised reference curve. The standardised reference curve, shown in Graph 5.3, is moved towards the calculated TL line, until the following parameters are met:

- The maximum deficiency in any one-third octave band does not exceed 8 dB, and
- The sum of the deficiencies at all one-third octave band frequencies is equal to or less than 32 dB.

Measured data points that lie below the reference curve are classed as deficiencies. Only these points are considered in the fitting procedure.

Once the shifted STC curve meets these criteria, the single number STC rating is the value indicated by the reference curve at 500 Hz.



Graph 5.3: Reference curve for airborne sound transmission class rating calculation[52]

The slope of the R_w and STC reference curves are slightly different, with the STC reference curve slightly steeper at lower frequencies.

5.3.3 Weighted suspended-ceiling normalised level difference rating

To calculate the weighted suspended-ceiling normalised level difference, $D_{n,c,w}$, the sound reduction through the plenum sound path is calculated as per ISO 10848-2:2006 *Acoustics – Laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms*

– *Part 2: Application to light elements when the junction has a small influence*[53]. The calculated TL curve is compared to the standardised curve shown in Graph 5.3. Once the condition of unfavourable deviations outlined in section 5.3.1 are met for calculating the movement of the standardised graph, the $D_{n,c,w}$ is the value given at 500 Hz of the moved curve.

5.3.4 Ceiling attenuation class rating

The calculation of the plenum sound path transmission loss to determine the single number ceiling attenuation class (CAC) rating is defined in ASTM E1414-11a *Standard Test Method for Airborne Sound Attenuation Between Rooms Sharing a Common Ceiling Plenum*[47]. The TL curve from these calculations are compared to the standardised reference curve shown in Graph 5.4. Once the conditions described in section 5.3.2 are met for the movement of the graph, the CAC single number rating is the value given at 500 Hz of the moved curve.

5.4 Transmission loss of suspended ceilings

As described in Chapter 1, ceiling tiles can be classified as either porous ceiling tiles, mineral fibre ceiling tiles, or composite ceiling tiles. For TL prediction modelling and measurements, a conventional single panel TL model (shown in Figure 5.1), can be expanded to a suspended ceiling grid, when measuring the sound travelling through the grid one way (shown in Figure 5.2). The transmission loss through the plenum sound path is shown in Figure 5.3, which is described as the flanking sound path over a separating wall between two rooms, or sometimes plenum sound path.

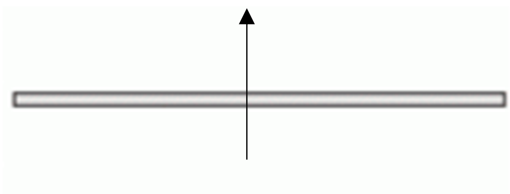


Figure 5.1: Single panel conventional transmission loss model

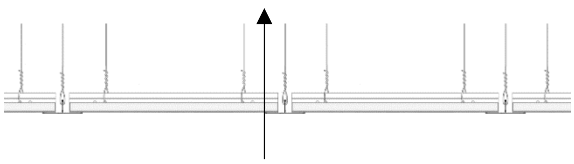


Figure 5.2: Transmission loss through a suspended ceiling system

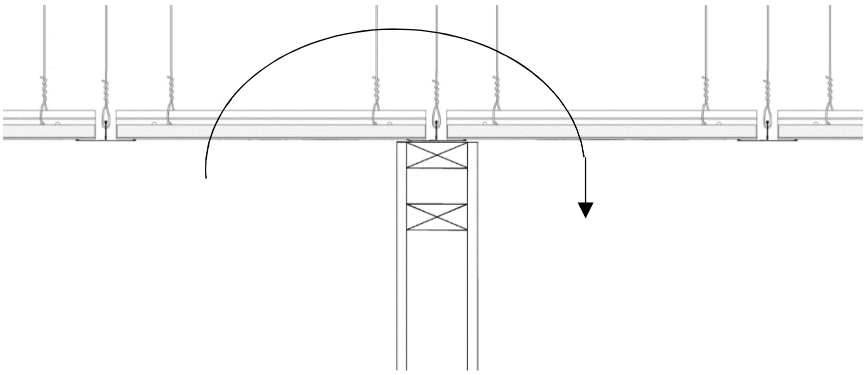


Figure 5.3: Sound transmission path when measuring the plenum sound path

5.4.1 Single panel sound transmission

Single panel TL can be defined as the sound lost through a single monolithic sheet of a given thickness that separates two discrete areas. These panels are generally used to separate non-noise sensitive areas within a building to give some privacy (for example a glazed wall). Generally in this application, other parameters (aesthetic, movement, or visual) are more vital than acoustic parameters. Unless heavy products that are relatively thick are used (such as filled concrete block), single panels offer little acoustic separation between spaces.

A single panel transmission loss can be related to a suspended ceiling system when considering sound travelling through one way (noise just from the plenum going into the space below, such as from a fan coil unit). Different elements need to be considered when determining the overall TL of a suspended ceiling when sound travels through a single way such as the ceiling tile, suspended ceiling grid, seal between the ceiling tile and grid, absorption in the plenum, and leakage around the ceiling tile.

5.4.2 Plenum sound path sound transmission

The plenum sound path is defined as the sound path from one room, through a suspended ceiling system into a plenum, through the plenum, and back through the suspended ceiling into an adjacent room. The transmission of sound through this path is dependant not only on the transmission loss of the suspended ceiling but the propagation of sound through the plenum, absorption in the plenum, and sound field in the plenum space.

5.5 Prediction of transmission loss

The prediction of the sound travelling between rooms through the plenum sound path has not been widely research or documented. Currently, there is only one empirical model, by Mariner, which uses a staged approach using current diffuse field, transmission loss, and sound propagation model to calculate the TL of sound through the suspended ceiling system, across the plenum (both direct and reverberant), and back through the suspended ceiling system. This model has many assumptions and employs equations from different prediction models, however it is the most thorough model available.

To predict the TL, an attenuation factor is required for the loss of sound through the suspended ceiling. This takes into account both the sound level difference between the two sides of the suspended ceiling, and the absorption of the ceiling tile. The sound power that is radiated by the suspended ceiling is divided equally between directly going to the adjoining plenum space, and reflected off the walls or roof to the adjacent plenum space.

The TL of a single panel system on the other hand has been widely researched, and models to predict the TL of single panels are reliable when compared to measured results. Early prediction models were developed by Cremer[50]. These models were further developed by London[19], Sewell[54], Sharp[55, 56], and Davy[57], as well as other various authors. Each author developed the model further, providing progressively more accurate prediction of the TL of a single panel system.

Before complex models were developed, basic TL calculations were used. These calculations assumed a single panel of infinite size, and very thin, such that the TL is purely through the mass reactance[14, 50]. This model does not take into account other material properties including stiffness of the panel, damping in the system, and the partition size. These models are called the “mass law” as the increasing the mass of the product will increase the TL. This model is only accurate at the low frequencies where the sound transmission is forced through the partition.

When stiffness is introduced into the TL model, it reveals a coincidence behaviour in the panel (ENC, Cremer 1942), due to bending harmonics. With the introduction of the stiffness of the panel to the model the results align significantly better to measured results of single and double panel systems. To predict the fourth region, above the coincidence dip of the panel system, a damping loss factor is required. This allows the increase shown above the coincidence region to be accurately predicted, and better align with measured results[58, 59].

Later TL models incorporated the finite behaviour of the panel (as all panels have a set width and height). These models showed an increased TL at the low frequencies compared to infinite panels which gave better agreement with measured results. Finite and infinite panel TL exhibits similar trends at, though, and above the coincidence region.

London[19], Sewell[54], Sharp[55-56], and Davy[57] expanded the finite panel TL models for both single and double panels. The Davy model used in this research, was initially published in 1990[57]. Davy's theory was further refined through a series of published papers[60, 61, 62, 63, 64], which mainly focused on double panel partitions, but also considered, in part, single panel partitions.

Davy's TL model is an adaption of the Cremer model, and while previous authors limited the integration angle of sound wave incidence on the panel to better align with measured results, Davy's single panel models did not use a limiting angle. The limiting angle was accounted for by using a single sided radiation efficiency model. A single sided radiation efficiency model includes an allowance for shear and bending wave propagation through the single panel structure.

5.6 Measuring transmission loss

There were two methods available for determining the TL of a suspended ceiling when sound travels through a single time. These were using a standard wall TL facility to measure the TL of a vertical suspended ceiling grid, or place a suspended ceiling grid in a floor/ceiling test facility. The University of Canterbury does not have a floor/ceiling test facility, so the method chosen for this research was a vertical suspended ceiling grid.

To measure the TL of a suspended ceiling grid between rooms a specialist Ceiling Flanking Noise (CFN) facility is used. This facility takes into account the transmission of sound into the plenum through the suspended ceiling system, sound being dissipated as it propagates through the plenum, and then the sound transmission back through the suspended ceiling system into an adjacent room.

5.6.1 Transmission loss facility

The TL facility at the University of Canterbury measures the TL of panels when mounted vertically as a wall between a reverberation room and a semi-anechoic room. The tests are conducted using an intensity probe to ISO 15186-1 *Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity Part 1: Laboratory measurements*[65].

A sound source is located in the reverberation room and multiple microphones are used to measure the sound pressure level. The reverberation room has been determined as being sufficiently diffuse previously[48] and the sound pressure located on the partition side facing the reverberation room is uniform[66]. An intensity probe is then used in the semi-anechoic room to measure the sound power emitted from the partition.

5.6.2 Ceiling flanking noise (CFN) facility

While the standard TL facility is useful to measure sound propagating through an element a single time, when sound travels through the plenum sound path, sound travels through a suspended ceiling twice, and propagates through the plenum. The transmission loss measured in this scenario requires a more detailed analysis of how sound is transferred though a suspended ceiling and the leakage that is associated with the suspended ceiling system.

A CFN facility is used to determine the sound TL of a suspended ceilings and ceiling tile systems between two adjacent rooms, where the main sound path is through the plenum, above the separating wall. This is done by constructing two reverberant rooms side-by-side with the separating wall being constructed so that it does not meet the roof. A suspended ceiling is then constructed through the two spaces such that it is flush with the top of the separating wall. This facility takes into account factors that are not present when the grid is measured vertically in a typical TL facility, such as the plenum absorption and the load imposed on the grid.

The construction, and measurement technique used to determine the TL of suspended ceiling between two adjacent rooms are described in both ISO 10848-2:2006, and ASTM E1414-11a. The ISO standard was developed in Europe, and is most commonly used in European countries. The ASTM Standard was developed in North America, and is adopted mostly throughout the Americas. Outside Europe and America, there are few CFN facilities. The CFN facility developed for this research is constructed and commissioned to ASTM E1414-11a.

To measure the TL through this path, a sound source is set up in one room and the sound pressure level at different positions in both the source room and adjacent receiving room are measured. The reverberation time in the receiving room is also measured to calculate the average absorption coefficient of all surfaces. The TL can then be determined by subtracting the sound pressure level measured in the receiving room from sound pressure level measured in the source room, allowing for the absorption in the receiving room. This technique is considered to be the most accurate way to determine the TL of a suspended ceiling system when the plenum sound path is the major contributing factor to the overall sound transmission between spaces.

5.6.3 Measurement repeatability

To the author's knowledge, there has been no published independent round-robin measurements using CFN facilities, and therefore the typical repeatability between CFN facilities is unknown.

ASTM International organised a four laboratory measurement comparison of two different ceiling tile systems: a 16 mm wet formed mineral fibre ceiling tile, and a 25 mm glass fibre ceiling tile. Multiple tests were conducted at each of the four laboratories. These results are incorporated into ASTM E1414-11a. From these results, this standard recommends that when commissioning a CFN facility, these two types of ceiling tiles are used to ensure that repeatability and reproducibility can be achieved. However, as mentioned in Chapter 1, mineral fibre can vary between manufacturers and the transmission loss of a 16 mm mineral fibre ceiling tile can vary, depending on its internal structure. This also holds true for glass fibre ceiling tiles. The ASTM round robin measurements found that the repeatability limit (difference between tests completed by the same operator, of the same laboratory, on the same day, using the same equipment) was greater 1.0 dB, and can vary as much as 5 dB for mineral fibre and 3 dB for glass fibre. The reproducibility (difference between two tests for the same product, by two different operators, using different laboratories, and different equipment) has a large deviation, between 1.5 dB and 12 dB for mineral fibre and 2.5 dB and 11.5 dB for glass fibre ceiling tiles[47].

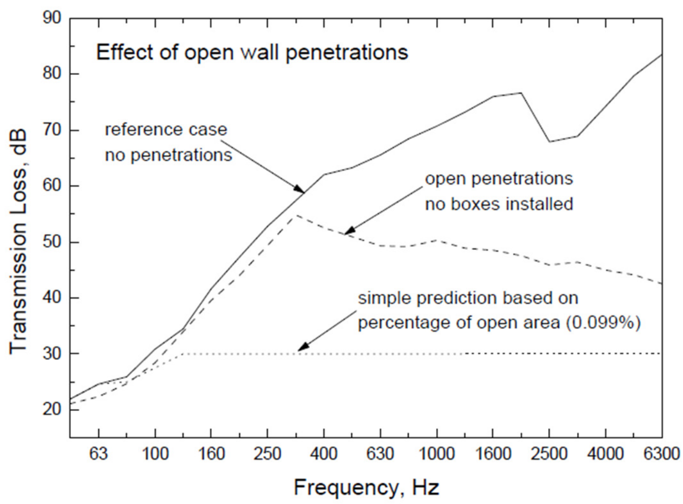
As mineral fibre can have a large variation between manufacturers, test data was sourced for a mineral fibre ceiling tile that had been tested at another CFN facility. It was concluded that if the results of this mineral fibre ceiling tile can achieve similar results to the manufacturer's data, it would give confidence in the commissioned facility. This approach is instead of using a random 16 mm mineral fibre ceiling tile, which could have very different material properties to that used by the ASTM E1414-11a round robin measurements.

5.7 Previous research

5.7.1 Previous research on transmission loss

While the TL of single and double panel walls can be predicted with some confidence using current models, the effects of penetrations and gaps within these walls have not been as rigorously researched. Penetrations (such as light switch boxes, power points, or gaps under doors) in wall systems can significantly reduce the TL rating of the wall system. With even a small open area within a wall (less than 1 %), the TL is reduced to no more than 20 dB[14]. This effect is even more pronounced if the hole is by the edge of a wall, as there are reflections from the surrounding surfaces that can increase the sound transmission between rooms two-fold[14].

Mechel and Oldham[67, 68] studied the reduction of slits and cylindrical shaped openings in a single panel wall system. Mechel found that the depth of the slit or opening was one of the most important factors when considering the reduction in TL from penetrations in a wall. Mechel[67] with further analysis by Oldham[69], found that for frequencies greater than a quarter of a wavelength of the depth of the opening, the openings were highly detrimental to the transmission loss. For opening sizes up to a quarter of a wavelength, the decrease in performance was directly related to the size of the opening compared to the overall partition area[67-68, 70].



Graph 5.4: Transmission loss of a wall with no penetrations and a penetration 75 mm by 45 mm penetration on both sides of the wall (open to the cavity)[70]

Nightingale and Quirt[70] measured two different wall systems with three different power point box configurations. The two walls were:

- Single stud wall (with and without fibrous insulation to the cavity), with a double layer of 13 mm plasterboard to either side of the 90 mm timber frame, and
- Double stud wall, separated by a 25 mm cavity between the frames, and two layers of 13 mm plasterboard either side of the system.

The three power outlet box locations were:

1. Directly opposite each other,
2. Opposite each other, offset 350 mm in the same stud bay
3. Opposite each other offset in different stud bays

The three different electrical box configurations are shown in Figure 5.4.

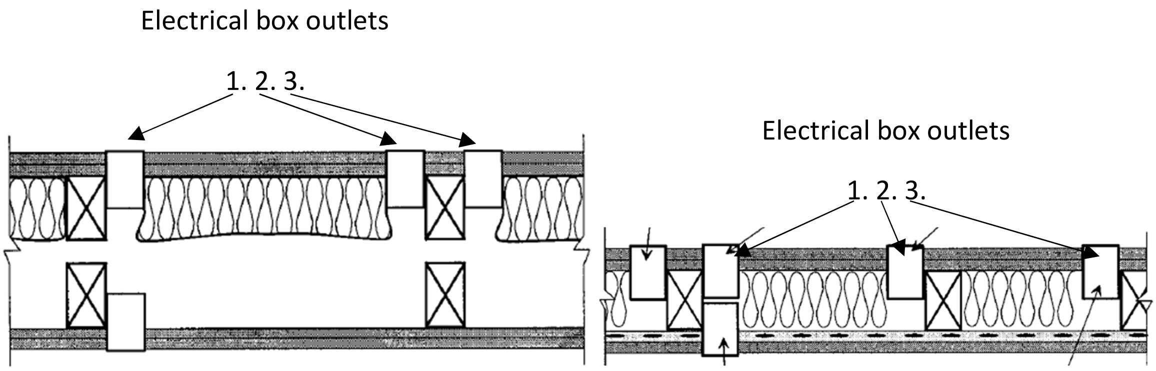
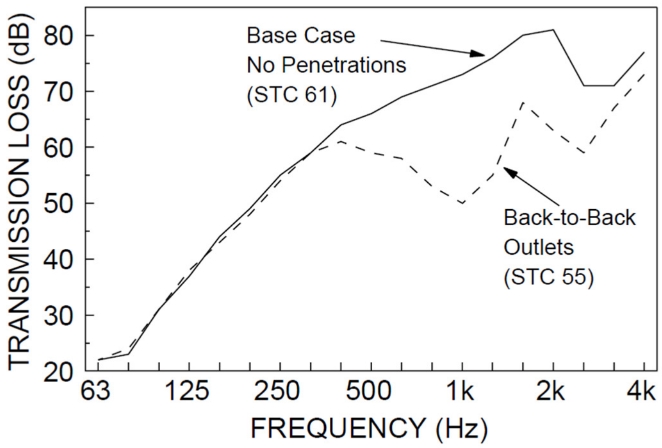


Figure 5.4: Diagram of the layout of the power outlet boxes within a double and single stud wall. Note that only one of the upper power outlet box layouts were tested at any one time[70]

The TL of the double stud wall, with fibrous absorption in the cavity, and without any penetrations was STC 61. When electrical outlet boxes were installed back-to-back, the transmission loss reduced to STC 55. This degradation was less apparent when the electrical outlet boxes were offset in the same stud bay (STC 60). An acoustic separation of STC 61 was achieved when the electrical outlet boxes were offset in adjacent stud bays, which was the same as if there were no penetrations[70]. The transmission loss curves for no penetrations and for back-to-back electrical boxes are shown in Graph 5.5 below.



Graph 5.5: Transmission loss for no penetration (solid line) and for back-to-back electrical boxes (dashed line) installed in a double stud wall[70]

The reduction in TL in single panels and through penetrations and openings in the surface can be translated to the TL of a suspended ceiling system. As described above, the TL of a single panel assumes that it is homogenous over the entire area, and has no openings or other elements included within it. A suspended ceiling is constructed of individual ceiling tiles (typically 1200 mm x 600 mm), installed in a metal grid suspended from the structure above. With this system there are sound transmission paths both through the grid itself, through the ceiling tile, and also through the spaces between the ceiling tile and grid.

To the author's knowledge there is no published research on the TL through a suspended ceiling in isolation. Manufacturers of floor systems sometimes test their system with and without a suspended ceiling below to see the improvement with one installed. However details of the actual ceiling tile product is rarely given, and therefore it is difficult to determine with any certainty the performance of the ceiling tile or suspended ceiling system.

5.7.2 Previous research on the plenum sound path

The first reported research completed using a CFN facility was by Hamme in 1959. This research was conducted in a CFN facility developed by Acoustical Materials Association (AMA) for the AMA–1–II–1967 draft standard[71]. Hamme tested two ceiling tile products (denoted Material "A" and Material "B"), as well as plasterboard ceiling tiles for control. Material "B" achieved a high TL at frequencies above 500 Hz when compared to that of the plasterboard ceiling tile. This additional TL was attributed to the added absorption from the back face of the Material "B" ceiling tile together with the absorption from the exposed edges of the ceiling tiles. However this increase in TL was only present in Material "B", and not in Material "A". The difference was not discussed in the paper. More knowledge of the constructions of the products would need to be known to draw any conclusions from this.

Further research conducted by Hamme[1] considered the effects of penetrations in the suspended ceiling, absorption added to the plenum perimeter walls, and installing a barrier above the separating wall. From tests conducted in the same CFN facility, it was found that if an open penetration (such as a return air grille) was installed in the suspended ceiling a few feet (half a metre) or less from the separating wall, there was a large increase in the sound transmitted between spaces. The increase in sound transmission measured by Hamme was approximately 5 – 10 dB at all frequency bands. The overall shape of the transmission loss curve stayed approximately the same, as shown in Graph 5.6. With the penetration further than one metre away from the wall, Hamme measured little difference when a penetration was made in the suspended ceiling[72].

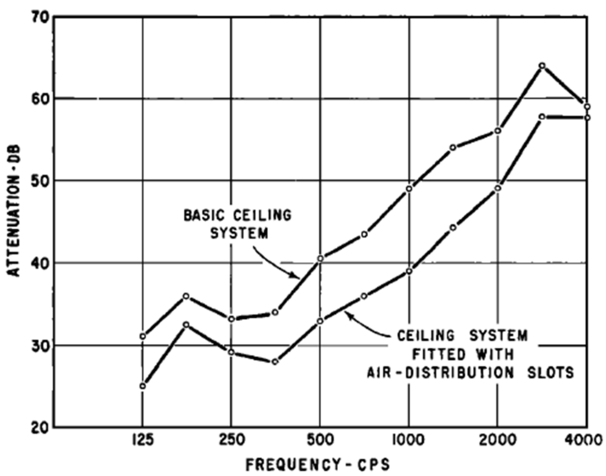


FIG. 10. Effect of utilizing plenum for air distribution through a suspended ceiling.

Graph 5.6: Effect of an open air return grille fitted in the suspended ceiling within 1.0 metre of the separating wall[1]

Hamme then experimented with installing absorption on the plenum perimeter walls (as this was not a requirement in the AMA Standard). This was to account for a larger plenum space as it would absorb sound rather than reflect sound, therefore acting like a typical plenum space where sound can propagate over large distances. The addition of the absorption on the plenum perimeter walls increased the overall transmission loss by approximately 3 – 10 dB in each frequency band, with the highest change at the mid-frequencies, as shown in Graph 5.7[1].

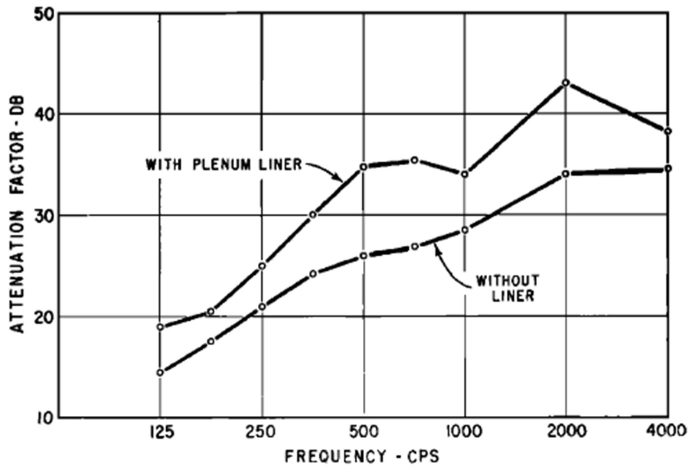


Fig. 2. Effect of plenum sidewall liner on the performance of a high flow-resistance ceiling erected at the 12-in. plenum depth.

Graph 5.7: Effect of absorption on the perimeter plenum walls with the same plenum depth[1]

Hamme installed a barrier in the plenum that spanned from the top of the separating wall to the roof, completely blocking the sound path through the plenum and effectively creating two independent spaces. With just the suspended ceiling or barrier installed, the sound transmitted between rooms was relatively high. Once both were installed the sound transmitted between rooms decreased significantly. The increase in TL over just the suspended ceiling or the barrier, to both, was approximately the transmission loss of both independently added together, as shown in Graph 5.8[1].

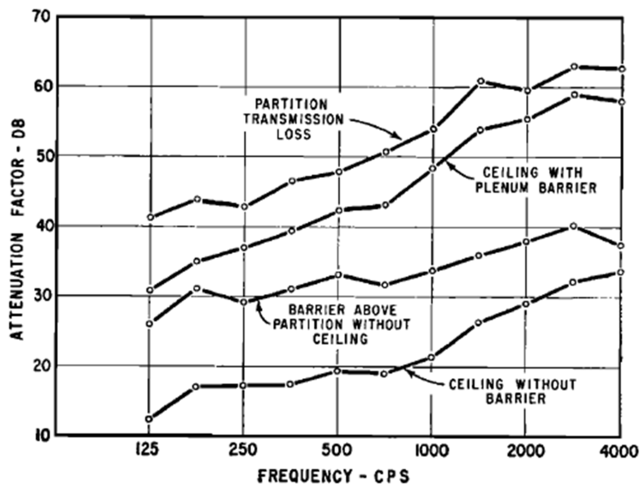


Fig. 11. Effect of plenum barrier in a ceiling-plenum system.

Graph 5.8: Effect of a plenum barrier on the transmission loss for a suspended ceiling[1]

The CFN facility that Hamme constructed was also able to accommodate plenum depths ranging from 12 to 30 inches (300 mm to 760 mm). Hamme found that when perimeter absorption was added to the plenum the change in plenum depth did not have a significant effect on the overall TL. It was concluded that with a product that has a high sound absorption installed around the perimeter of the plenum, the results are comparable for any plenum depth within the range of 12 to 30 inches. Graph 5.9 below shows that the solid bold line is relatively flat for high (lower curve) absorption coefficient ceiling tiles, and low (upper curve) absorption coefficient ceiling tiles the TL curves are relatively flat when compared to the TL without plenum absorption (dashed line).

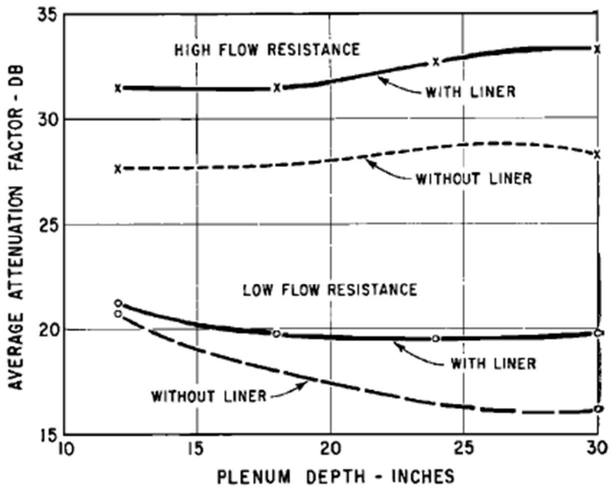
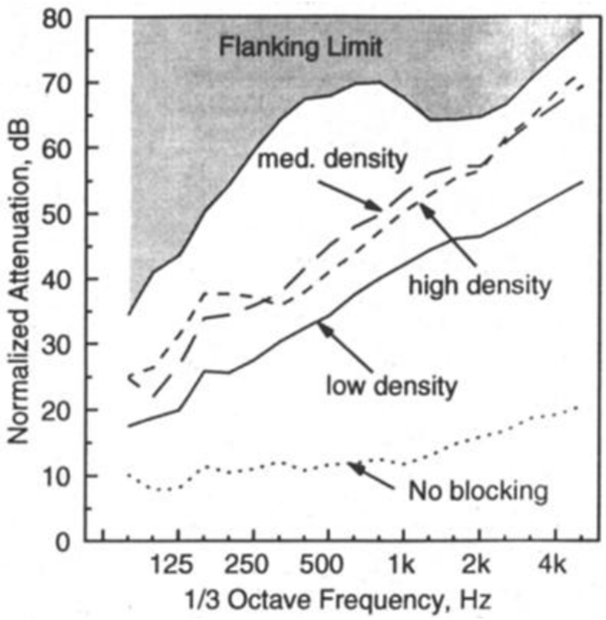


Fig. 4. Suppression of plenum-depth dependence by plenum sidewall liner.

Graph 5.9: Difference in transmission loss when considering absorption on perimeter plenum walls, depth of cavity, and high and low absorption ceiling tiles[1]

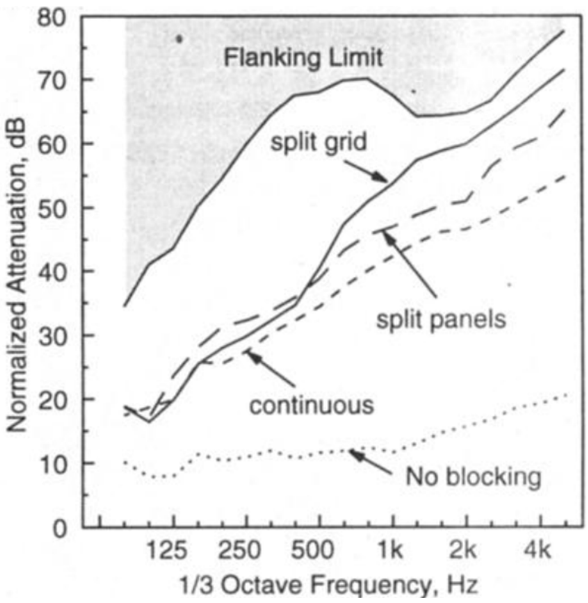
Halliwell and Quirt continued the research of Hamme, installing a separating element above the separating wall within the plenum. Halliwell and Quirt used absorptive glass fibre batts stacked between the top to the suspended ceiling and roof[2] to act as a barrier between each adjacent rooms. Glass fibre batts were used as these could be moulded around penetrations (including mechanical ductwork, hydraulic services, and electrical cabling) rather than installing a solid wall system, which would have to be cut and sealed to accommodate services.

Three insulation batts with different properties were used. Each was found to have similar flow resistivity for the same thickness. The medium density batts were the thickest batts tested in the study. As the medium density batts had a higher sound transmission loss at mid frequencies (between 316 Hz, and 2,000 Hz), the thickness of the batts was expected to be one of the controlling factors[2]. The difference in the transmission loss of the three thermal insulation batts, installed above the separating partition, is shown in Graph 5.10[2].



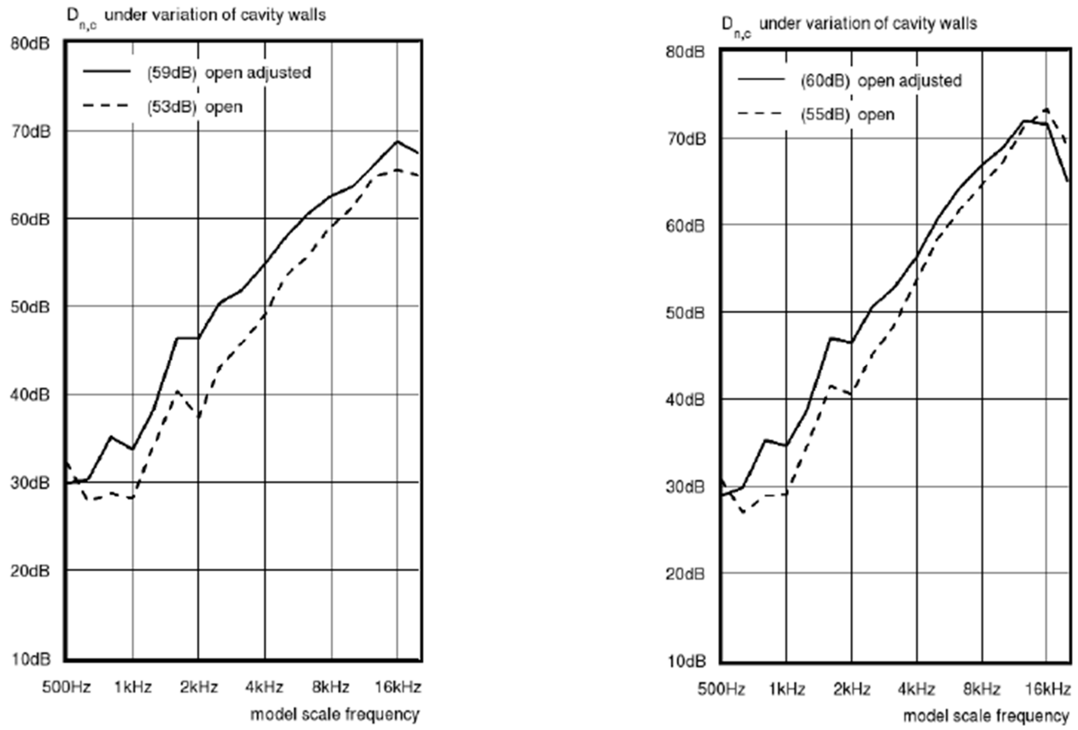
Graph 5.10: Transmission loss of thermal insulation batts of different densities installed above the separating wall within the plenum[2]

Halliwell and Quirt also measured the effect that the suspended ceiling played on the sound transmission between spaces. A continuous ceiling, split panels and two separate grids were installed to find the difference in sound transmission with compressed glass fibre batts installed above. Graph 5.12 shows the effect that splitting the panel (large dashed line), having a continuous grid (small dashed line), and having two separate grids installed which butt to the side of the wall (rather than laid on top of the wall). While the TL is similar at low frequencies at mid and high frequencies, the TL of the split grid increased dramatically when compared to the continuous grid. This was attributed to vibration transfer through the continuous grid. These vibrations would not be transferred in a split grid, and are even further reduced, if two separate grids were installed. With two unconnected grids, no vibration transfer can occur and therefore at the higher wavelengths where this is of concern no flanking can take place[2].



Graph 5.11: Transmission loss of different grid and ceiling tile set-ups within a CFN facility[2]

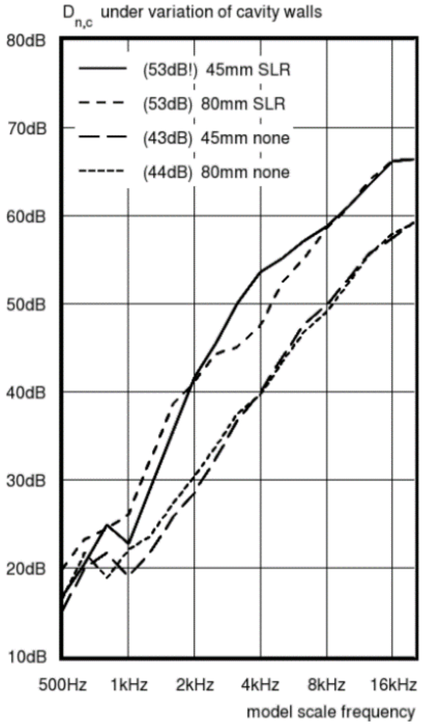
Extending the idea of adding absorption to the plenum perimeter walls, Royar and Schmelzer[73] analysed the difference in having an open sided plenum to that with fibrous insulation on all four sides, with and without porous ceiling tiles installed. This was to compare the effect of an open plenum with one that simulated an open plenum (using absorption on the perimeter walls). Graph 5.13 shows the TL difference between absorption on the perimeter walls (solid line) compared to no plenum absorption (dashed line). The left graph is for ceiling tiles that are not absorptive, and the right graph is for ceiling tiles that are absorptive[73]. The graph shows that with reflective ceiling tiles the difference between having an open plenum side and absorptive plenum sides is high (up to 8 dB at any single octave band). This is less prominent with a porous ceiling tile installed[73]. Due to the open nature of the plenum, and the difference in size between the plenum perimeter openings and the room in which the model is built, impedance differences in the air may reflect some sound back into the space, decreasing the overall sound transmission. This would not happen with absorption, as the sound would be absorbed rather than reflected by the impedance mismatch between the two air volumes. This impedance mismatch would not be present in a typical plenum as the plenum is continuous, rather than open to a much larger room.



Graph 5.12: Transmission loss of a suspended ceiling when the plenum perimeter walls are removed, and when the plenum perimeter walls are lined with absorptive material[73]

In addition, Royar and Schmelzer compared the effects on TL of the difference in suspended ceiling height (45 mm to 80 mm, at a 1:10 scale) with and without absorption to three perimeter walls to find if the cavity depth changes the sound transmission between the spaces. Graph 5.13 shows the difference between a 45 mm and 90 mm plenum depth with absorption (shown as solid and mid-dashed line, denoted at 45 mm SLR and 80 mm SLR in graphs), and without absorption (large and small dashed line, denoted as 45 mm none and 80 mm none)[73]. It was concluded that when absorption was present on the walls there was little difference in sound transmission between the rooms for a different depth cavity[73].

It is important to note that the facility that Royar and Schmelzer used for their research was a 1:10 scale model. In addition, it allowed the removal of plenum side walls, and different plenum depths, so therefore did not comply with the relevant standards but probably provides an indication of performance in a full scale CFN facility.



Graph 5.13: Difference in transmission loss between a lined and unlined absorption plenum at 45 mm and 90 mm plenum depths[73]

5.8 Summary

The TL of homogenous panels has been extensively researched. The effects of leaks in panels have been considered previously, no specific work concerning leaks within a suspended ceiling has been identified. The ceiling tiles sit on the suspended grid system and are mounted with clips being used to hold the ceiling tiles such that they do not fall down in the event of an earthquake. However, significant leaks are likely to occur between the ceiling tiles and suspended grid system.

There are two international standards (ISO 10848-2:2006, and ASTM E1414-11a) that prescribe the construction and measurement methodology for the determination of the TL of sound through the plenum sound path between adjacent rooms, called a ceiling flanking noise facility. Single number ratings can be used to quickly compare two products. The R_w parameter was developed for the ISO 10848-2:2006 measurement methodology, with the CAC rating developed for the ASTM E1414-11a measurement methodology.

Extensive research and testing has been completed on single panel homogeneous systems. However, the TL of a suspended ceiling, taking into account the TL of the grid, ceiling tile, and leakage around the grid has not been published. Hamme's research on reducing sound through the plenum sound path has focused on the addition of air diffusers in the suspended ceiling and adding a barrier in the plenum, over the separating wall. Halliwell and Quirt further developed a barrier in the plenum by installing thermal insulation above the separating wall in the plenum and compressing it.

6.0 Design Requirements of the CFN Facility

6.1 Overview

A CFN facility is a test space specifically constructed to measure how much sound is transferred between two adjacent rooms when the only significant sound transmission path is through a common ceiling plenum. Measuring the TL in a CFN facility takes into account factors that are not present when testing the TL of a suspended ceiling system using a TL facility, including flanking noise at the top of the wall, plenum absorption, and insertion loss of the sound travelling through the plenum.

To the author's knowledge, there are no CFN facilities in New Zealand. There is currently one CFN facility in Australia, located at the Acoustic Laboratory at Architectural Ceiling Systems Pty Ltd, in Western Australia. Worldwide there are only a few CFN facilities and the majority of these facilities are in private laboratories.

The CFN facility at the University of Canterbury[74] was commissioned and shown to comply with ASTM E1414-11a. This chapter describes the requirements of ASTM E1414-11a, the difference between the ASTM E1414-11a and comparable ISO 10848-2:2006 standard, as well as the commissioning of the CFN facility at the University of Canterbury. This chapter concludes with the results of the commissioning process.

6.2 CFN facilities

Research or results of testing conducted using a CFN facility are not widely published and the details of these facilities less so. Published research on the construction of a CFN facility was found for a laboratory set up at the Housing and Building Research Centre (HBRC) in Egypt, which was published in 2012. Previous research has been conducted in CFN facilities but these facilities were generally not constructed to any standard.

Hamme conducted research in a CFN facility built by the AMA before any standards for CFN facilities were promulgated. The overall internal floor area of this facility was 10 feet (3.05 metres) by 28 feet (5.83 metres), and 11 feet 6 inches (3.40 metres) high, which included the plenum area. Hamme went on to describe this facility as having a heavy partition wall, which has an adjustable height to change the plenum depth. The suspended ceiling covered an area of 10 foot by 14 foot (3 metres by 4.26 metres) in each room. This facility could accommodate a plenum depth between 12 and 30 inches (300 mm to 760 mm). The wall is described as being a 'heavy partition wall' so probably has a high transmission loss[1].

Halliwell and Quirt developed a CFN facility that was constructed in accordance with the first draft of ASTM E1414, developed in 1990 (Halliwell 1991). This facility measured 8.7 metres long, by 4.5 metres wide, and was 3.55 metres high. The suspended ceiling was installed 2.8 metres above the floor, with a plenum depth of 0.75 metres. All the plenum perimeter walls were lined with absorptive batts, which had an absorption coefficient of 0.85 for the frequency bands between 125 and 4,000 Hz[2]. The separating wall of the facility was described as a two layer damped steel sandwich, which was separated by a cavity filled with glass fibre. This cavity ranged from 75 mm at the top to 300 mm at the bottom. The flanking limit of the CFN facility was measured in-situ, and is shown in Table 6.1 below[2].

Table 6.1: Flanking limit of Halliwell and Quirt facility (taken from Figure 4[2])

Frequency, Hz	125	250	500	1000	2000	4000
Normalised Attenuation, dB	44	58	68	68	66	75

Royar and Schmelzer developed a 1:10 scale CFN facility, to the European ISO 140-9 Standard (updated to ISO 10848-2), with the exceptions that the plenum depth may be varied, and the perimeter walls of the plenum are able to be removed. While the construction detail of the separating wall is not clearly stated, it can be deduced that it comprises of two walls of 20 mm MDF either side of a timber stud with mineral fibre in the cavities on each room. Therefore the separating wall was a quadruple panel wall system. Two separate rooms were constructed and pushed together, with a gap left between the rooms so that no structure-borne sound could be transferred. The facility was installed on three vibration mounts to further attenuate structural vibration borne sound[73].

A CFN facility has recently been constructed at the HBRC in Egypt, in 2012. This facility has been constructed and commissioned to ASTM E1414-11a. The facility had an overall length of 10.0 metres, width of 5.0 metre, and a height of 4.0 metres. This was split into two rooms, one 6 metres long and one 4 metres long. The height of the suspended ceiling was 3 metres above the floor of the facility, with a plenum height of 1 metre[75]. This facility would not strictly meet ASTM E1414-11a as the plenum depth is too large and the difference in room volumes being over 10 % (among other factors). The separating wall between the two rooms was constructed of 2 layers of 13 mm gypsum plasterboard on 40 mm steel studs, with 40 mm of 50 kg/m^3 mineral fibre insulation installed in the cavity. The studs were separated by 100 mm, so they weren't touching, and therefore structural vibration could not be transferred between rooms. This wall tested in situ achieved an STC of 65[75].

6.3 ASTM E1414-11a construction and measurement requirements

ASTM E1414-11a describes the construction of a CFN facility to simulate a pair of adjacent rooms separated by a partition that only extends up to the ceiling height and so share a common ceiling plenum. The CFN facility is constructed such that the only significant sound path between the spaces is though this common ceiling plenum.

While this Standard (and the similar ISO Standard), were developed to measure the sound transmission between rooms, this facility can also be used to assess the performance of penetrations in a suspended ceiling (such as grilles, recessed lights, and speakers). In addition, in-ceiling treatments to reduce sound through the plenum can also be explored.

A summary of the construction, commissioning, and measurement requirements of a CFN facility for compliance with ASTM E1414-11a are outlined in Table 6.2.

Table 6.2: Requirements of a CFN facility constructed and commissioned to ASTM E1414-11a

Property	**ASTM E1414-11a**
Room dimensions	7.5 ± 1.5 m long 4.65 ± 0.23 m wide 3.65 ± 0.15 m high
Plenum depth	760 ± 25 mm at the separating wall, 760 mm ± 65 mm in all other areas
Plenum width	At separating wall 4.30 m ± 0.02 m All other places same as room
Plenum lining	All perimeter plenum walls lined with acoustic absorption no less than 76 mm thick, Absorption coefficient not less than 0.65 at 125 Hz, and 0.8 at 250 – 4,000 Hz centre frequency bands
Surface absorption coefficients	Average sound absorption coefficient on wall, roof, and floor no greater than 0.1 at 125 Hz to 4,000 Hz centre frequency bands
Difference in room volume	< 10 %
Diffusivity	Sufficiently diffuse. Recommended 8 m^2 diffuser panels in both rooms
Sample size	Covering entire ceiling
Steady state noise level in receiving room	≥10 dB above background noise level
Minimum number of microphone positions	Enough to adequately sample the sound field in each room
Specified placement of microphones	≥ 0.75 m from reflecting surface ≥ 1.5 m from sound source ≥ 0.75 m apart
Flanking paths (including separating wall, external walls)	Sound power through ≤ 10 dB than through plenum
Signal spectrum	Random noise with continuous distribution between 125 Hz and 4,000 Hz centre frequency octave bands
Background noise level	≤ 10 dB lower than noise received from receiving room
Ceiling installation	In accordance with ASTM C636[76]
Reported values	Normalized ceiling attenuation ($D_{n,c}$) calculated for each 1/3 octave bands between 125 Hz and 4,000 Hz centre frequency bands. CFN rating using reference curve

6.3.1 Room dimensions

The overall dimensions for the CFN facility are to be measured internally and to be within the tolerances given. The overall length of the facility, which includes both rooms the width of the separating wall and any structural discontinuity, is 7.5 metres ± 1.5 metres. The overall width of each room is required to be the same, with a width of 4.65 metres ± 0.23 metres, The total height of the facility is required to be 3.65 metres ± 0.15 metres, which includes the height of the room and the plenum.

While not described in clause 7.1.1 *room construction* of ASTM E1414-11a[47], Figure 1 of the standard shows that each room is required to have a length differing no more than 10 %. Figure 1 in ASTM E 1414-11a is reproduced in Figure 6.1.

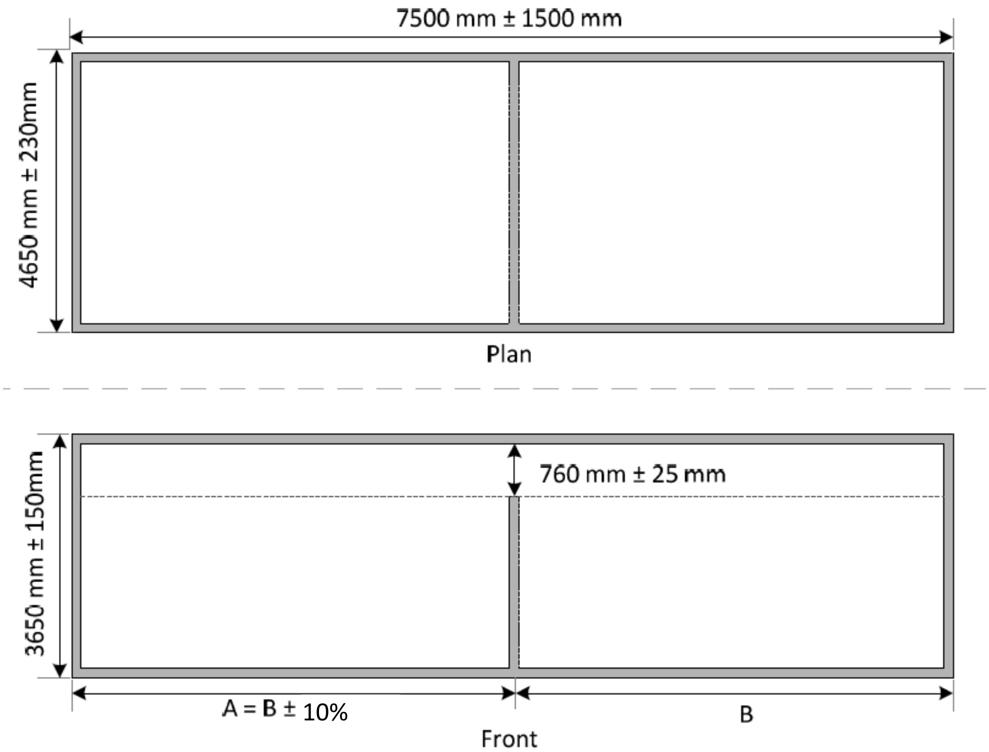


Figure 6.1: Dimension requirements of ASTM E1414-11a

6.3.2 Plenum

The requirements of the plenum are split into three components, the height, the width, and plenum perimeter absorption.

The plenum height is required to be 760 mm ± 25 mm at the separating wall. The height requirement is relaxed at all other areas of the plenum space to 760 mm ± 65 mm. The plenum height is restricted at the separating wall because the sound is transmitted between the rooms at this location, so the plenum depth must be closely comparable between laboratories.

The width of the plenum is required to be the width of the room at all positions (4.65 metres ± 0.23 metres) apart from above the separating wall where it is required to be reduced in width. The plenum width above the separating wall is required to be reduced to 4.3 metres wide ± 0.02 metres (20 mm). ASTM E1414-11a recommends this is achieved by the use of pilasters on each side of the separating wall that span from the separating wall to the roof above.

Finally, ASTM E1414-11a requires that all perimeter plenum external walls are to be lined with fibrous acoustic absorption that is a minimum of 76 mm thick and has a minimum absorption coefficient at each octave band centre frequency octave band outlined in Table 6.3.

Table 6.3: Minimum absorption coefficients of the plenum wall lining[47]

Octave Band Centre Frequency, Hz	125	250	500	1000	2000	4000
Absorption coefficient, α	0.65	0.8	0.8	0.8	0.8	0.8

6.3.3 Surface absorption coefficients

The sound absorption coefficients of the surfaces below the suspended ceiling are required to be less than 0.1 at all octave band centre frequencies between 125 Hz and 4,000 Hz. The surface absorption coefficient of the roof, above the suspended ceiling, within the plenum are also required to have an absorption coefficient of less than 0.1 at each of these frequency bands.

The absorption coefficients are required to be measured in accordance with the test method outlined in ASTM C423.

Due to the absorptive nature of ceiling tiles that are installed in the suspended ceiling grid, the suspended ceiling system is not included in the average absorption coefficient within the space. However an increase in absorption in just this plane will result in a change in the diffusivity of the sound field and increase the overall absorption within each room.

6.3.4 Diffusivity

Each of the two rooms are required to be *"sufficiently diffuse"*[47]. The test method outlined in ASTM E1414-11a to ensure that the sound field is sufficiently diffuse is via compliance with the precision requirements of clause 11.3 of ASTM E1414-11a. The Standard goes on to recommend that three stationary diffusers are to be added to each room such that the total single sided surface area is 8 m^2 in each room, and each diffuser has a minimum width of 0.7 metres. The diffusers are to be placed such that they do not shield the ceiling specimen from the direct sound from the loudspeaker.

The precision requirements of clause 11.3 state that the *"precision statement was determined through the statistical examination of a total of 408 analytical results, submitted by the four participating laboratories, on two ceiling materials"*[47]. While no precision requirements are given in clause 11.3, it is assumed that compliance with precision statement is what is being referred to for diffusivity. The precision statement refers to two different ceiling tile specimens: a 16 mm mineral fibre, and a 25 mm glass fibre ceiling tile specimen. The precision statement gives average TL values, repeatability standard deviation, reproducibility standard deviation, repeatability limits, and reproducibility limits for both of these ceiling tile products.

It has been assumed that if one or both of the ceiling tile specimens are tested in a CFN facility the results should be within the reproducibility limit of the average TL, and the repeatability should not differ more than the repeatability limits when measured multiple times on the same and different days. As noted above, mineral and glass fibre can differ significantly between manufacturers, such that if two different manufacturer's ceiling tile was tested in a CFN facility that were the same product and thickness, the results could vary.

ASTM E1414-11a notes that as the majority of the absorption within the room will be located on the ceiling and therefore it is difficult to obtain a sufficiently diffuse sound field due to one surface being highly absorptive. While the standard recommends that 8 m^2 of diffusers are installed, if measurements comply with the reproducibility and repeatability limits outlined in Table 2 of ASTM E414-11a, and reproduced in Table 6.4 and 6.5 with diffusion panels less than 8 m^2, then the sound field can be classed as 'sufficiently diffuse'.

Table 6.4: Average transmission loss, repeatability limits, and reproducibility limits for 25 mm glass fibre ceiling tiles[47]

Frequency, Hz	Average transmission loss, dB	Repeatability limit, dB	Reproducibility limit, dB
125	19.64	1.86	2.50
160	21.04	2.09	4.88
200	21.71	2.93	9.98
250	24.48	2.66	4.40
315	25.54	3.14	7.17
400	24.32	1.18	8.16
500	20.69	1.94	6.14
630	22.11	2.76	3.16
800	30.39	2.18	3.62
1000	31.21	1.08	5.86
1250	31.10	1.79	8.52
1600	33.52	1.61	11.53
2000	34.70	1.71	10.67
2500	37.96	2.09	9.52
3150	40.54	1.16	10.47
4000	43.17	1.47	9.63
CAC	27.8	1.6	6.3

Table 6.5: Average transmission loss, repeatability limits, and reproducibility limits for 16 mm mineral fibre ceiling tiles[47]

Frequency, Hz	Average transmission loss, dB	Repeatability limit, dB	Reproducibility limit, dB
125	21.74	5.39	12.17
160	25.19	2.73	9.67
200	26.68	1.23	12.08
250	27.02	1.34	6.26
315	26.50	1.29	9.56
400	29.87	1.41	4.99
500	31.55	1.95	5.96
630	33.25	1.18	8.30
800	36.62	1.21	7.09
1000	40.42	1.70	4.97
1250	44.31	1.58	3.48
1600	47.26	1.20	1.53
2000	48.81	2.08	7.19
2500	51.11	1.01	6.60
3150	52.76	1.31	4.75
4000	53.73	2.15	5.77
CAC	36.8	1.1	7.4

6.3.5 Sample size

The suspended ceiling system installed to house the ceiling tiles for testing is required to be equal to the area of both the room's length and width, taking into consideration the following:

- The perimeter absorption shelf that is installed around the perimeter of both rooms, which supports the perimeter absorption in the plenum.

- The area of the adapter cap if testing an interrupted suspended ceiling system (two independent suspended grids).

- The area of any filler ceiling tiles. These are installed where the width is less than 100 mm, and only used at the end walls, farthest away from the separating walls.

- Area of the pilasters installed to reduce the plenum width at the separating wall.

The suspended ceiling grid must be installed to, and comply with, the requirements of ASTM C636-13 *Standard Practice for Installation of Metal Ceiling Suspension Systems for Acoustical Tile and Lay-In Panels*[76]. The installation of the ceiling tiles or in-ceiling treatment recommended in ASTM E1414-11a is to be installed as per the manufacturer's recommendations.

6.3.6 Steady state noise level during collection

During measurements, the noise level measured in the receiving room, when the speaker is played in the source room, is required to be a minimum of 10 dB above the background noise level during the running of each test. If any external noise source is within 10 dB of the sound level of the loudspeaker, the test must be restarted.

6.3.7 Microphones

ASTM E1414-11a does not give a minimum or maximum number of microphone positions required to adequately measure the sound field. This standard requires the number of microphone positions used to be sufficient to satisfy the precision requirements outlined in section 11 of ASTM E1414-11a, and outlined in Tables 6.4 and 6.5 above.

The standard allows either fixed or microphones on a rotating boom to be used. If fixed microphone locations are used, then the number of microphones used should adequately sample the sound field. Fixed microphones must be a minimum of 0.75 metres away from any reflecting surface (walls, floor, ceiling, or diffuser), 1.5 metres away from the loudspeaker, and 0.75 metres from other microphone locations. If a rotating boom is used, the boom radius is required to be not less than 0.75 metres, and must not come closer than 1.5 metres to the loudspeaker.

The measurement time must be adequate to accurately estimate the space-time average noise level. If a rotating microphone is used the measurement time must be equal to or greater than that for one boom rotation.

6.3.8 Flanking sound paths

The construction of the separating and all external walls, floors, and the roof between the two rooms is required to have a TL high enough such that sound travelling through the plenum sound path is 10 dB or higher than through any other sound paths.

The standard requires flanking to be analysed before any tests are undertaken. This can be done by blocking the sound path through the plenum such that this path is at the required rating of the wall plus 10 CAC points above the highest expected ceiling tile specimen to be tested.

ASTM E1414-11a also recommends that there be a structural discontinuity between each of the rooms. This reduces any structure-borne sound transmission between the rooms.

6.3.9 Test signal

The signal generator that is used to generate the sound through the loudspeaker must broadcast bands of random noise with a continuous distribution over all the test frequency bands. The test bands are required to be one-third octave bands between 100 Hz to 5,000 Hz.

6.3.10 Background noise level

The background noise level (any noise source other than the loudspeaker used for the tests) must be 10 dB or more lower at each test one-third octave band frequency (100 Hz to 5,000 Hz) than that received from the loudspeaker in the source room. The standard requires this to be routinely checked to ensure that the background measurements do not interfere with the measurement results. If background noise levels are more than 10 dB above the signal then the sound power of the loudspeaker must be increased and the tests redone until the background noise levels do not affect the measurements.

6.3.11 Suspended ceiling system installation

The installation of the suspended ceiling grid must be strict accordance with ASTM C636-13[76]. The mounting of ceiling tiles are recommended to be installed as per the manufacturers guidelines.

For the suspended ceiling grid, the hangers are required to be spaced at 1200 mm centres on main runners for loadbearing suspended ceilings. Cross runners are to be supported by main runners. The hanger wire is to be made from a minimum of 2.70 mm (number 12 gauge) galvanised mild steel wire. The hangers are required to be at an angle of 60 to 90 degrees from the horizontal unless bracing is used. The main runners must be level so they are within the tolerance of a 6 mm maximum deflection over a 3,000 mm length. This is also required for cross runners. Carrying channels have a more stringent deflection limit of 3.2 mm over a length of 3,600 mm. All fixtures are to be mounted such that they do not compromise the performance of the suspended ceiling and do not exceed the deflection limits or the total dead load of the system.

Ceiling tiles are to be installed as per the manufacturer's guidelines and specifications.

6.3.12 Results

The requirements for the reporting of testing are specified in clause 10 *Report* of ASTM E1414-11a. The results of the tests are to be displayed as one-third octave band TL (in dB) values, as well as the calculated CAC single number rating as described in section 5.3.4, and detailed in ASTM E413-10. If the TL is affected by any flanking sounds or background noise disturbance, then this needs to be noted.

A full description of the suspended ceiling and ceiling tile combination for testing is required, which includes the size of the grid and ceiling tiles, the type of ceiling tiles installed, and data for the ceiling tiles (such as thickness, weight, facing material, seal to the suspended ceiling, and the like). In addition, the suspended ceiling system is to be described as a three letter system:

- First letter: "C" or "I" – Continuous or Interrupted suspended ceiling system
- Second Letter "E" or "C" – Exposed or concealed suspended grid
- Third letter "T" "F" "N" "H" "V" "X" – Where the first three describe the cross section of the concealed suspended system of Tee splines, Flat spines, or No splines. H designates that hold-down clips were used for securing the ceiling tiles, and V designates that ventilation, or light fixtures were used in the suspended ceiling. If V is used, the location, and type must be accurately described. X is used where other variations form a typically installed suspended ceiling system.

A description of the plenum space is required that describes the condition of the plenum (height, absorption, dimension etc.) during testing. The report must also detail any additions to the plenum space (such as additional absorption, in-ceiling treatment, ductwork etc.), beyond the requirements of ASTM E 1414-11a. The environmental conditions (temperature, humidity, and barometric pressure) of the receiving room are to be reported, as well as any limitations of the test methodology as described in Section 5 of ASTM E1414-11a.

6.4 Differences between ASTM and ISO CFN facilities

There are two recognised international standards that govern the construction, commissioning, and determination of the TL of a suspended ceiling system. These are ASTM E1414-11a and ISO

10848-2:2006. The differences between these two standards are compared in Table 6.6 below. The CFN facility at the University of Canterbury was commissioned to ASTM E1414-11a.

Table 6.6: Comparison of construction and testing of CFN facilities based on ISO and ASTM Standards

Property	**ASTM E1414-11a**[47]	**ISO 10184-2:2006**[53]
Room dimensions	7.5 ± 1.5 m long 4.65 ± 0.23 m wide 3.65 ± 0.15 m high Length of rooms not to differ by more than 10 %	9.0 ± 1.0 m long ≥ 3.5 m wide ≥ 2.3 m + plenum height
Plenum depth	760 ± 25 mm at the separating wall, 760 mm ± 65 mm in all other areas	Between 700 mm & 800 mm
Plenum width	At separating wall 4.30 m ± 0.02 m All other places same as room	Same as room
Plenum lining	All perimeter plenum walls lined with acoustic absorption no less than 76 mm thick, Absorption coefficient not less than 0.65 at 125 Hz, and 0.8 at 250 Hz – 4,000 Hz centre frequency bands	Both widths and one length of plenum covered in absorption. Absorption coefficient of plenum absorption not less than 0.65 at 125 Hz and 0.8 at 250 Hz – 4,000 Hz centre frequency bands
Surface absorption coefficients	Average sound absorption coefficient on wall, roof, and floor no greater than 0.1 at 125 Hz to 4,000 Hz centre frequency bands	N/A
Difference in room volume	N/A	> 10 % minimum of 50 m^3
Diffusivity	Sufficiently diffuse. Recommended 8 m^2 diffuse panels in both rooms	Addition of diffusing elements until SPL is not influenced by any longer
Sample size	Covering entire ceiling	Covering entire ceiling
Steady state noise level in receiving room	≥10 dB above background level	≥10 dB above background level
Minimum number of microphone positions	Enough to adequately sample the sound field in each room	≥ 5 microphones
Specified placement of microphones	≥ 0.75 m from reflecting surface ≥ 1.5 m from sound source ≥ 0.75 m apart	≥0.7 m from reflecting surface ≥1.0 m from sound source ≥ 0.7 m apart

		≥1.0 m from specimen
Flanking paths (including separating wall, external walls)	Sound power through ≤ 10 dB than through plenum	Sound power through have no effect on measured quantities
Signal spectrum	Random noise with continuous distribution between 125 Hz and 4,000 Hz centre frequency octave bands	Random noise with continuous distribution between 100 Hz and 5,000 Hz centre frequency octave bands
Background noise level	≤ 10 dB lower than noise received from receiving room	≤ 15 dB lower than noise received from receiving room
Ceiling installation	In accordance with ASTM C636	In accordance with manufacturer specifications or ISO 2785
Reported values	Normalized ceiling attenuation ($D_{n,c}$) calculated for each one-third octave bands between 125 Hz and 4,000 Hz centre frequency bands. CFN rating using reference curve	Calculated normalized flanking level ($D_{n,f}$) calculated for each one-third octave bands between 125 Hz and 4000 Hz. $D_{n,f,w}$ rating using reference curve

The main differences between the ASTM and ISO standards are the room dimensions, plenum absorption, microphone positions, and background noise levels.

The ISO standard requires a longer facility, 9.0 ± 1.0 m, and only limits the width to greater than 3.5 metres compared to the ASTM standard that requires the CFN facility to be 7.5 ± 1.5 m long, and has a more stringent width requirement of 4.65 m ± 0.23 m. The height of the facility for both standards is specified differently, with the ISO standard requiring the room to be greater than 2.3 metres to the underside of the suspended ceiling, plus the depth of the plenum (between 700 mm and 800 mm), whereas the ASTM standard requires the overall height of the facility to be 3.65 metres ± 0.15 m, which includes the plenum of 760 mm ± 25 mm. There is some ambiguity in the ASTM E1414-11a standard when reviewing the length of each room. ASTM E1414-11a does not state that the two rooms are required to differ in length by 10 %, however Figure 1 in ASTM E1414-11a shows a diagram stating A = B + 10%, where A and B are the two lengths of the room. It is stated later in the standard that the rooms are not to differ by more than 15 % in length. The ISO requirement recommends that there is a difference in room volume between the source and receiving room, but does not state a difference in length for the rooms. The ASTM E1414-11a standard also requires that the width of the wall decreases at the separating wall to 4.3 m ± 0.02 m, whereas the ISO 10848-2:2006 standard does not require this reduction in width.

Acoustic absorption is required on the perimeter of the walls within the plenum for both standards. ASTM E1414-11a requires all perimeter walls to be lined with acoustic absorption that is a minimum of 76 mm thick and has an absorption coefficient of no less than that outlined in Table 6.3. The absorption coefficient requirement is the same in ISO 10848-2:2006, however the absorption on the perimeter walls is limited only to the two width walls (end walls) and one length wall (side walls). One side wall is required not to have any absorption on it.

ASTM E1414-11a does not give a maximum difference for the room volumes. ISO 10186-2:2006 gives a maximum difference in room volumes of 10 % and a minimum volume of both rooms of 50 m^3. The room volumes are required to have a diffuse sound field, although a sound field cannot be completely diffuse due to the large absorption area from the ceiling tiles. ASTM E1414-11a recommends 8 m^2 of diffusing elements and compliance with the reproducibility limit for mineral fibre and glass fibre ceiling tiles. ISO 10184-2:2006 recommends that the sound field is measured with increasing amounts of diffusing elements until the sound field is not influenced by the addition of more diffusing elements. This is required in both rooms.

For both standards, the suspended ceiling grid and ceiling tile product are required to cover the entire ceiling area.

The specification for microphone positions is stringent in ASTM E1414-11a as these are required to be further from reflecting surfaces, further apart and further from the sound source than the ISO Standard. ASTM E1414-11a does not have a requirement for a minimum distance away from the test specimen, unlike ISO 10848-2:2006 has. For the ISO standard, the microphones are required to be positioned a minimum of 1.0 m from the test specimen. ISO 10848-2:2006 requires a minimum number of microphones (5 or more), whereas ASTM E1414-11a requires enough microphone positions to adequately sample the sound field in each room to meet the precision requirements of the Standard.

ISO 10848-2:2006 has a more stringent background noise level limit of 15 dB or greater below the test signal at each one-third octave band at the test frequencies measured in the receiving room. ASTM E1414-11a only requires the background noise to be 10 dB below the test signal at the one-third octave band test frequencies in the receiving room.

The final main difference is the normalisation term used for the equivalent sound absorption area for the calculation of the normalised ceiling attenuation (or flanking) level. ISO 10848-2:2006 uses reference area of 10 m^2, where ASTM E1414-11a standard uses a 12 m^2 reference area. Due to the larger equivalent sound absorption area used in the ASTM calculations, higher results (by approximately 0.79 dB) are expected when measurements are conducted in a CFN facility commissioned to the ASTM Standard[73]. The calculation of the single number rating (CAC for ASTM E1414-11a, and $D_{n,c,w}$ for ISO 717-1:2000), requires the fitting of different curves to the test results. The two standards use different curves and therefore will produce slightly different single number ratings.

6.5 Commissioning of the CFN facility

To ensure the CFN facility developed at the University of Canterbury complies with ASTM E1414-11a, a series of tests were undertaken. Table 6.7 describes the requirements of ASTM E1414-11a, with the results from the commissioning tests and measurements. The requirements and how these were met are described in detail below.

Table 6.7: Requirements of a CFN facility constructed and commissioned to ASTM E1414-11a

Property	ASTM E1414-11a	CFN Facility at the University of Canterbury
Room dimensions	7.5 ± 1.5 m long 4.65 ± 0.23 m wide 3.65 ± 0.15 m high	7.42 metres 4.77 metres 3.51 metres
Plenum depth	760 ± 25 mm at the separating wall, 760 mm ± 65 mm in all other areas	750 mm at the separating wall 750 mm all other places
Plenum width	At separating wall 4.30 m ± 0.02 m All other places same as room	4.31 metres
Plenum lining	All perimeter plenum walls lined with acoustic absorption no less than 76 mm thick, Absorption coefficient not less than 0.65 at 125 Hz, and 0.8 at 250 – 4,000 Hz centre frequency bands	90 mm thick absorption installed around plenum, absorption coefficients meet that requires (see section 6.5.2)
Surface absorption coefficients	Average sound absorption coefficient on wall, roof, and floor no greater than 0.1 at 125 Hz to 4,000 Hz centre frequency bands	Average absorption coefficients measured in situ, all less than 0.1 (see section 6.5.3)
Difference in room volume	<10 %	Both rooms have same width and height, differ in length by 0.4 metres. Volume difference 0.52 m^3

Diffusivity	Sufficiently diffuse. Recommended 8 m^2 diffuse panels in both rooms	Diffusivity measured three different ways, found that three diffusing panels totalling a single sided area of approximately 5 m^2 was sufficient in both rooms
Sample size	Covering entire ceiling	Covers entire ceiling, apart from 90 mm to 100 mm wide plenum absorption shelf.
Steady state noise level in receiving room	≥10 dB above background noise level	Measured receiving room noise level was checked after each test to ensure 10 dB above background noise level. If not, then tests were redone.
Minimum number of microphone positions	Enough to adequately sample the sound field in each room	Measurements found that 5 microphone positions were sufficient.
Specified placement of microphones	≥ 0.75 m from reflecting surface ≥ 1.5 m from sound source ≥ 0.75 m apart	All microphone positions met these requirements.
Flanking paths (including separating wall, external walls)	Sound power through ≤ 10 dB than through plenum	Tested flanking sound paths by pressure – pressure measurement method, achieved a STC 61 rating for all other sound paths.
Signal spectrum	Random noise with continuous distribution between 125 Hz and 4,000 Hz centre frequency octave bands	Signal spectrum used for all tests was white noise generated by a Burel and Kjær PULSE system.
Background noise level	≤ 10 dB lower than noise received from receiving room	Measured background noise level of less than the inherent noise of the test microphones.
Ceiling installation	In accordance with ASTM C636[76]	Installed in accordance with ASTM C636, and AS/NZS 2785 were required.
Reported values	Normalized ceiling attenuation ($D_{n,c}$) calculated for each one-third octave bands between 125 Hz and 4,000 Hz centre frequency bands. CAC rating using reference curve	Normalized ceiling attenuation ($D_{n,f}$) calculated for each one-third octave bands between 125 Hz and 4,000 Hz centre frequency bands. $D_{n,c,w}$ rating using reference curve

To fully comply with the criteria in ASTM E1414-11a, as outlined in Table 6.2, the CFN facility was required to be demountable and to be flat-packed so the facility could be relocated due to the rebuilding work currently happening at the University of Canterbury. This resulted in a lightweight construction being used for the CFN facility. The external walls and roof were constructed of 18 mm plywood either side of a 90 mm timber frame, with 90 mm fibrous insulation installed in the cavity. The floor was constructed of 18 mm MDF board over 90 mm timber joists. The separating wall was constructed of one layer of 13 mm Standard GIB plasterboard, 18 mm MDF, and 4 kg/m^2 mass loaded barrier on a single 90 mm timber stud with 18 mm plywood on a secondary 90 mm timber stud on the adjacent room. 90 mm fibrous insulation was installed in the cavity between the rooms. The two rooms, with half the separating wall in each room, are constructed separately and pushed together such that they were close, but not touching.

The facility was designed and constructed before the start of the research presented in this thesis without the input of the author. The commissioning process for each part of the CFN facility, outlined in Table 6.7, is described in detail below.

6.5.1 Room dimensions

The CFN facility is split into two rooms, the receiving room and the source room. Both rooms have a width of 4.77 metres and a height to the suspended ceiling of 2.74 metres above the floor. The length of the source room is 3.53 metres, with the length of the receiving room 3.57 metres. This gives a total volume of 46.13 m^3 for the source room, and 46.66 m^3 for the receiving room. The total length of the CFN facility is 7.42 metres, which includes the length of both rooms, the width of the separating wall, and the structural discontinuity. The total internal height of the CFN facility is 3.51 metres. These measurements are shown in Figure 6.2.

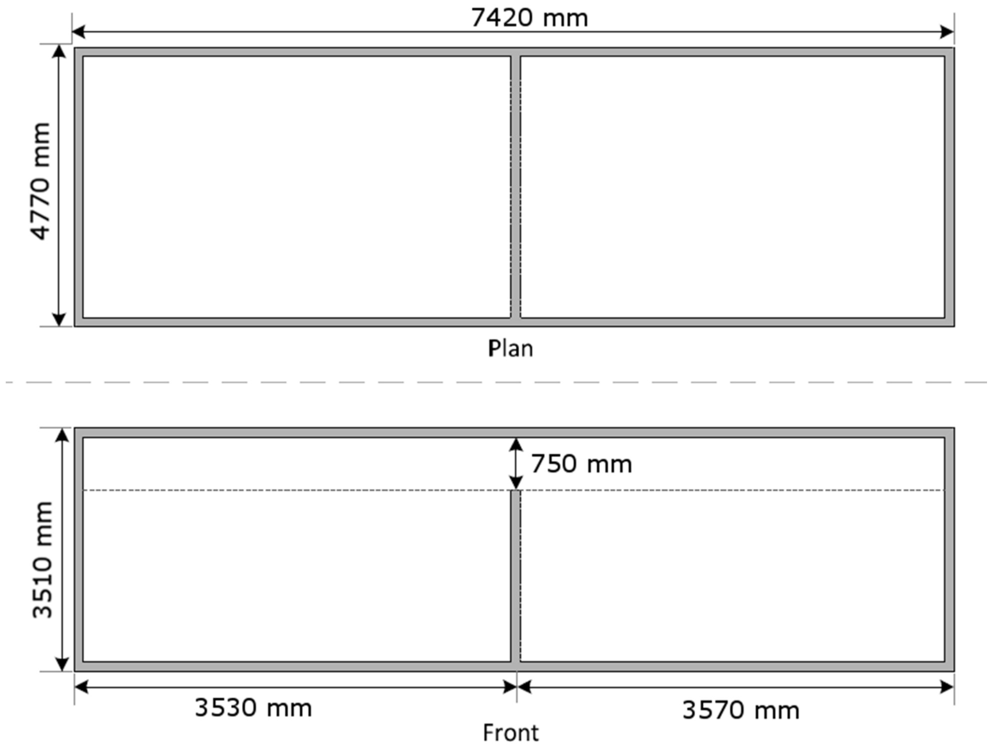


Figure 6.2: Dimensions of the CFN facility constructed at the University of Canterbury

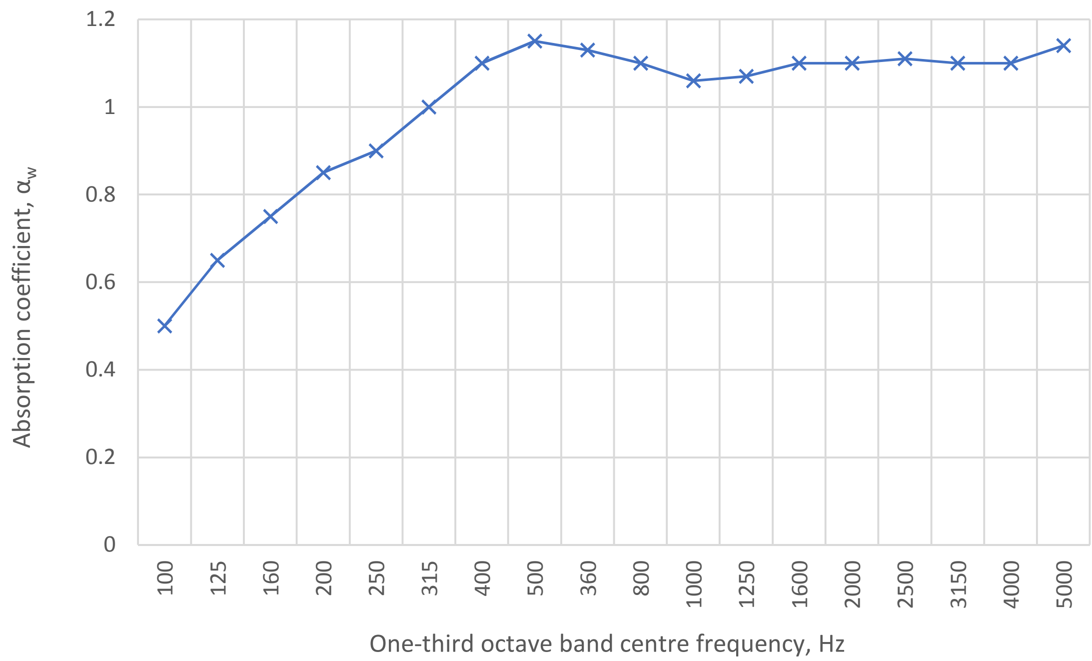
The overall dimensions of the CFN facility constructed at the University of Canterbury comply with the requirements described in ASTM E1414-11a.

6.5.2 Plenum

The plenum is the width and length of the facility (7.42 metres long, by 4.77 metres wide), except at the separating wall where it is reduced in width. At the separating wall, the plenum is reduced to 4.31 metres by the use of four pilasters, two installed in each room on each side of the separating wall. These are not touching, so the structural discontinuity between rooms is maintained. In total the pilasters are approximately 300 mm wide. The suspended ceiling is installed at the same height across the entire CFN facility, creating a plenum depth of 750 mm with a volume of 26.34 m^3.

The plenum perimeter walls are lined with 90 mm fibrous insulation, which covers the full height of the plenum (approximately 750 mm across the entire plenum) on all four perimeter walls. This plenum absorption sits on a 90 mm – 100 mm wide plenum perimeter shelf which is flush with the lower face of the suspended ceiling grid. This shelf is constructed of 35 mm thick pine timber with 4 kg/m^2 mass loaded barrier adhered to the plenum side. This was expected to have a TL of 10 dB or higher than any ceiling tile product that will be tested. The plenum absorption shelf does not protrude out wider than the pilasters.

The fibrous insulation was tested in a reverberation room prior to installation, and Graph 6.1, and Table 6.8 show the absorption coefficients for this product.



Graph 6.1: Absorption coefficient measured in accordance with ASTM E423-09a for 90 mm absorption added to the perimeter walls of the plenum

Table 6.8: Tabulated absorption coefficient measured in accordance with ASTM E423-09a for 90 mm absorption added to the perimeter walls of the plenum

Frequency, Hz	Absorption coefficient, α_w	Required absorption coefficient, α_w
125	0.65	0.65
250	0.90	0.80
500	1.15	0.80
1000	1.06	0.80
2000	1.1	0.80
4000	1.1	0.80

The plenum perimeter absorption was not installed around the pilasters that are installed at the separating wall, as Figure 3 in ASTM E1414-11a does not show the plenum absorption in this position. The perimeter absorption installed within the plenum is shown in Figure 6.3.

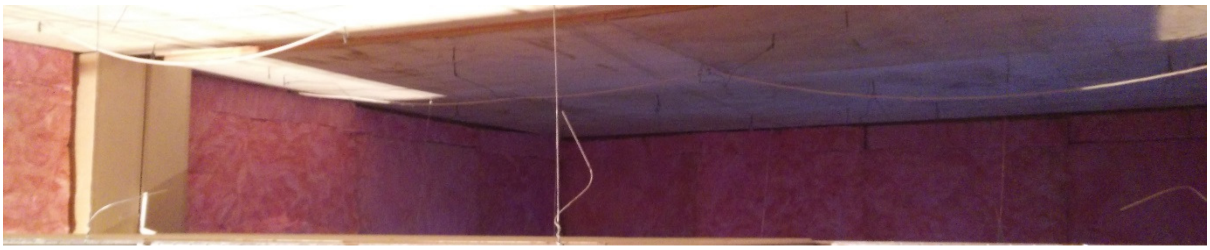


Figure 6.3: Fibrous acoustic absorption installed around the perimeter of the plenum

The plenum perimeter absorption installed within the CFN facility at the University of Canterbury complies with all the requirements of ASTM E1414-11a.

6.5.3 Surface absorption coefficients

Reverberation time measurements were conducted in both rooms, and the resultant equivalent absorption area was calculated using the method outlined in ASTM E2235 *Test method for determination of decay rates for use in sound insulation test methods*, and reproduced in Equation 6.1.

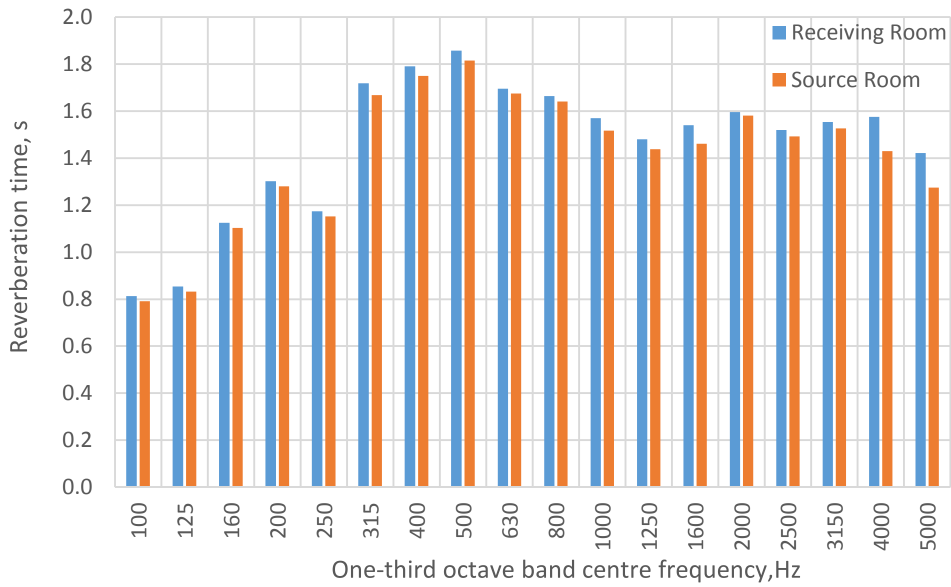
$$A = \frac{Vd}{c} \qquad \text{Equation 6.1}$$

Where A is the equivalent area of absorption in m², V is the volume of the room in m³, d is the decay rate in dB/s, using a 60 dB reduction divided by the measured reverberation time, and c is the speed of sound in seconds taking into consideration the ambient conditions. From this, the average absorption coefficients of the surfaces below the suspended ceiling were calculated using Equation 6.2.

$$A_\alpha = \frac{A}{S_t} \qquad \text{Equation 6.2}$$

Where A_α is the average absorption coefficients of the surface, A is the equivalent absorption area in m² calculated from Equation 6.1, and S_t is the total surface area of the room in m².

The reverberation time of the source and receiving rooms are given in Graph 6.2, and the calculated average surface absorption coefficients calculated are given in Table 6.9 below.



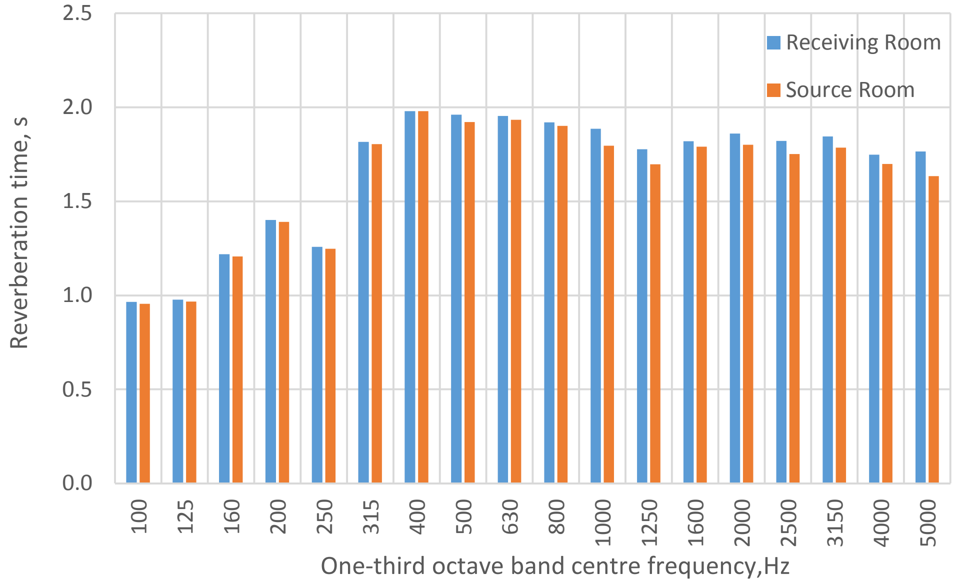
Graph 6.2: Reverberation time at one-third octave bands for the source and receiving room for the CFN facility at the University of Canterbury

Table 6.9: Average sound absorption coefficients of the surfaces below the suspended ceiling for the source and receiving room at the University of Canterbury

Frequency, Hz	Source room average area absorption coefficient, A_α	Receiving room average area absorption coefficient, A_α	Required average area absorption coefficient, A_α
100	0.12	0.12	
125	0.11	0.11	0.1
160	0.09	0.08	
200	0.07	0.07	
250	0.08	0.08	0.1
315	0.06	0.06	
400	0.05	0.05	
500	0.05	0.05	0.1
630	0.06	0.06	
800	0.06	0.06	
1000	0.06	0.06	0.1
1250	0.07	0.06	
1600	0.07	0.06	
2000	0.06	0.06	0.1
2500	0.06	0.06	
3150	0.06	0.06	
4000	0.07	0.06	0.1
5000	0.07	0.07	

The majority of the calculated average surface absorption coefficients of the surfaces in the source and receiving rooms within the CFN facility were less than 0.1. However at the low frequencies (100 Hz and 125 Hz) the average surface absorption coefficients were over 0.1 and therefore remediation measures were needed to ensure that the reverberation time was increased in these frequency bands to decrease the average surface absorption coefficients. To reduce low frequency absorption, the structure is required to be more rigid. The low frequency reverberation time may be increased by increasing the rigidity of the structure (by installing bracing on the walls, or internally lining both rooms with sheet steel). As a first approach, painting both rooms was undertaken and also the centre distance between screws was reduced, by adding a screw between each current screw on each floor and wall panel.

With this additional treatment the reverberation times in the source and receiving rooms were increased. The reverberation times for both rooms are shown in Graph 6.3, and the calculated average absorption sound absorption coefficients of the surfaces in the source and receiving room was recalculated, are shown in Table 6.10.



Graph 6.3: Reverberation time at one-third octave bands for the source and receiving room for the CFN facility at the University of Canterbury after additional screws were added, and both rooms painted

Table 6.10: Average sound absorption coefficients of the surfaces below the suspended ceiling for the source and receiving room at the University of Canterbury after additional screws were added, and both rooms painted

Frequency, Hz	Source room average area absorption coefficient, A	Receiving room average area absorption coefficient, A	Maximum allowable average area absorption coefficient, A_α
100	0.10	0.10	
125	0.10	0.10	0.1
160	0.08	0.08	
200	0.07	0.07	
250	0.08	0.08	0.1
315	0.05	0.05	
400	0.05	0.05	
500	0.05	0.05	0.1
630	0.05	0.05	
800	0.05	0.05	
1000	0.05	0.05	0.1
1250	0.06	0.05	
1600	0.05	0.05	
2000	0.05	0.05	0.1
2500	0.05	0.05	
3150	0.05	0.05	
4000	0.06	0.05	0.1
5000	0.06	0.05	

With the additional screws and with both rooms painted, the average sound absorption coefficients of the surfaces in the source and receiving room were reduced to 0.1 or below. There are slight differences between the source and receiving rooms as the receiving room received an additional coat of paint to the source room, which resulted in the reverberation time being slightly higher.

6.5.4 Diffusivity

Three different methods to assess the diffusivity of the sound field in each room of the CFN facility was used. ASTM E1414-11a only states that the CFN facility is required to be 'sufficiently diffuse'. To ensure that the facility is sufficiently diffuse, the precision requirements of section 11.3 of ASTM E1414-11a are met. The standard goes on to recommend 8 m^2 of diffusers in each room.

To evaluate the diffusivity of the sound field in each room, three different tests were carried out:

1) Adding diffusers to each room until the TL through the plenum sound path does not change (method outlined in ASTM E90-09 / ISO 10140:2010)[49, 77]
2) Adding diffusers to the room until the absorption coefficient of a standard piece of absorption product does not change (method outlined in ASTM E423-09a / ISO 354:2003)[12, 22]
3) Measuring the sound pressure level at a grid across each room with increasing amounts of diffusers.

Each of these were evaluated separately, to find the optimum number and area of diffusion panels in each of the rooms.

Once all sound transmission paths were evaluated, and exceeded the required TL as outlined in ASTM E1414-11a, the in ceiling treatment was removed, and 25 mm fibrous ceiling tiles were installed in the suspended ceiling grid. These ceiling tiles were used, as they provided minimal sound transmission between the rooms, however enough to examine the difference when diffusing elements were added to each space. In addition to meeting the precision requirements of ASTM E1414-11a, when adding diffusing elements to the room the TL should not change by more than the maximum deviations outlined within ISO 3741:1999 *Acoustics – Determination of sound power levels of noise sources using sound pressure – Precision methods for reverberation rooms*[78], shown in Table 6.11.

Table 6.11: Maximum allowable deviation for one-third octave bands

Central frequency (one-third octave band, Hz)	Maximum standard deviation (dB)
100 – 160	1.5
200 – 630	1.0
800 – 2500	0.5
3150 - 10000	1.0

Three sets of measurements were carried out with diffusers (single sided area of 2.0 m^2) progressively added to both the source and receiving rooms. The average TL results for the addition of diffusers into each space are given in Table 6.12. From these tests, increasing the diffusing panels from three panels to four panels increases the TL less than that outlined in Table 6.11, and the tests meets the precision requirements of ASTM E1414-11a both for reproducibility and repeatability.

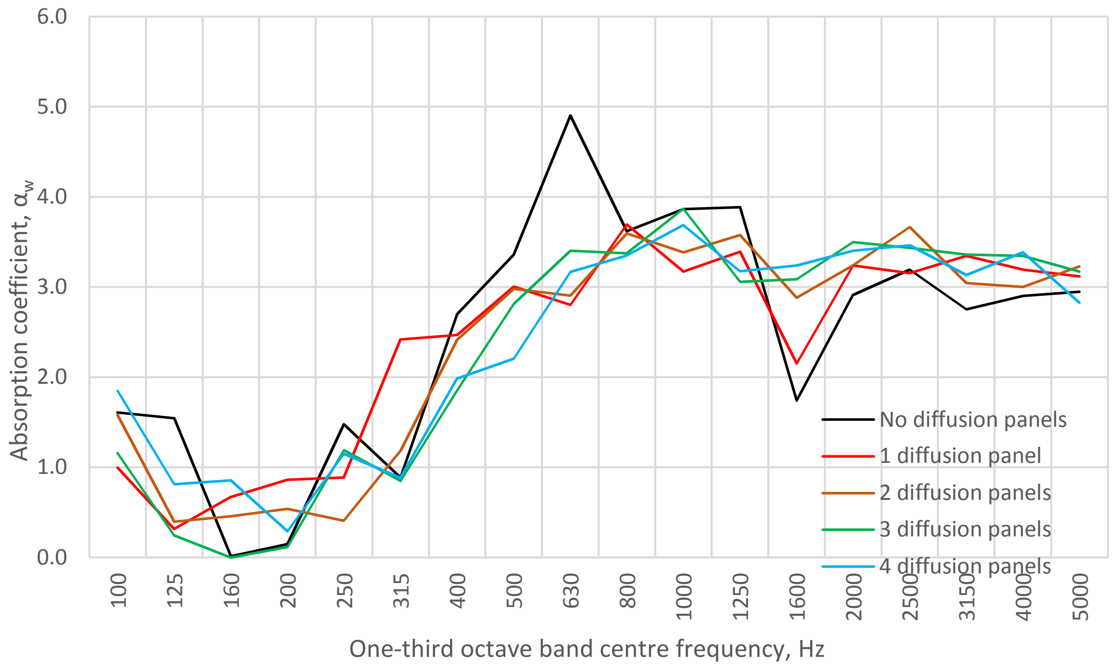
Table 6.12: Average TL of none to four diffusers to ensure a sufficiently diffuse field within the CFN facility at the University of Canterbury

Frequency, Hz	No diffusion panels installed	One diffusion panel installed	Two diffusion panels installed	Three diffusion panels installed	Four diffusion panels installed
125	16.5	19.1	18.9	19.7	19.6
160	17.3	19.6	18.6	21.1	21.0
200	19.9	21.3	20.9	21.8	21.8
250	22.6	24.3	23.9	24.5	24.5
315	25.1	25.3	24.8	25.7	25.7
400	21.9	22.9	23.5	24.5	24.5
500	19.5	20.6	20.6	20.8	20.8
630	20.3	21.7	21.7	22.2	22.2
800	29.1	29.8	29.8	30.5	30.4
1000	29.9	31.2	31.2	31.5	31.4
1250	29.7	30.9	31.0	31.3	31.3
1600	33.2	33.3	33.3	33.8	33.7
2000	33.6	34.1	34.5	34.9	34.9
2500	37.0	37.8	37.9	38.6	38.5
3150	39.4	40.3	40.4	41.1	41.1
4000	42.1	43.2	43.1	43.4	43.4

To provide a sufficiently diffuse sound field to comply with the precision requirements of ASTM E1414-11a by using the TL method, three individual diffusion panels are required that have a single sided area of 2.0 m².

Secondly, Annex A of ISO 354:2003 gives a method to check the diffusivity of reverberation room. While this room did not meet the requirements of ISO 354:2003 (reverberation time was too short, and volume too small), the test method should allow the difference in results between diffuser numbers to be seen. ISO 354:2003 recommends testing the absorption coefficient of a product that has an absorption coefficient of 0.9 or greater between 500 Hz to 4,000 Hz. A 50 mm polyester porous absorbing panel was used, that measured 2.0 metres long by 1.5 metres wide.

The absorption coefficient of the absorption product was measured with no diffusers, and up to four diffusers each with a single sided area of 2 m². The absorption coefficients are shown in Graph 6.4 below. With no diffusion panels, the absorption coefficient curve is relatively erratic. When two diffusers are installed in the room, most of the erratic nature of the absorption coefficient curve is removed. Once three or more diffusers were added to the room, the absorption coefficient did not significantly change, and therefore can be concluded that three diffusion panels are required in the space to ensure that the room is adequately diffuse.



Graph 6.4: Absorption coefficient of 50 mm polyester porous absorber panel with different amounts of diffusing elements installed in the CFN facility

The source room was used for this diffusion test. However the surface finishes were the same and the volume was similar in the receiving room so it was assumed that the same amount of diffusing elements would be required in the receiving room.

The spatial uniformity was the final test completed to quantify the diffuseness of the sound field in the CFN facility. 500 mm by 500 mm grid was marked out on the floor of the receiving room and sound pressure measurements were taken at all these locations while the loudspeakers was turned on in the source room (25 mm fibrous ceiling tiles were used to ensure an adequate sound level in the receiving room which was not influenced by any external noise level). The sound pressure levels were measured at all points with zero to four diffusing panels installed in the source and receiving room.

The maximum deviations given in ISO 3741:1999, and replicated in Table 6.11 above were used as a guide for assessing adequate diffusivity of the sound field. Once the sound pressure measurements did not differ by that outlined in in Table 6.11 above for all relevant frequencies when additional diffusion panels were added, this was assessed to be adequately diffuse. It was found that four diffusing panels were required to ensure that the diffusivity of the sound field was adequate.

Full results from the diffusivity testing are shown in Appendix A.X.

While four diffusing panels were needed when sound pressure levels were measured over the space, only three diffusion panels were required for the other two measurements, and for the TL measurement. The TL measurement, with three diffusion panels, also met the precision requirements of ASTM E1414-11a, so therefore three diffusing panels were installed in each room of the CFN facility at University of Canterbury during each test.

6.5.5 Sample size

The dimensions of the room allowed the suspended ceiling grid to be seven and a half ceiling tiles wide (each 600 mm) by three ceiling tiles long in each room (along the length of 1200 mm) i.e. 6 tiles long overall. A main 'T' member was installed on top of the capping that separates the source and receiving room. In this way, the ceiling tile products cover the entire ceiling, apart from a 90 to 100 mm wide plenum absorption shelf, which helps support the plenum absorption, an. Only whole or half ceiling tiles were used, so no ceiling tiles were less than 100 mm wide.

As the suspended ceiling grid was designed to have seven and a half ceiling tiles wide, the eighth ceiling tile was required to be cut in half to fit into the grid. In addition, four ceiling tiles were required to be cut to fit around the pilasters.

6.5.6 Steady state noise level during collection

A white noise signal was generated by a Bruel and Kjær PULSE system. The white noise was generated for a minimum of five seconds before measurements were started to ensure that the sound had sufficiently 'built up' in the source and the receiving room.

The background noise level was measured before the tests and the noise level measured in the receiving room was compared to that during the tests to ensure that the background noise level did not influencing the results. If the background noise level was within 10 dB of the measured noise level in the receiving room when tests were conducted, then the loudspeaker sound power was increased until the sound received in the receiving room was 10 dB or more above the background noise level.

6.5.7 Microphones

While diffusing elements were added to the room, as described in section 6.5.4, multiple microphones were used to measure the sound pressure level within the source and receiving rooms to ensure that accurate average sound levels in both rooms were recorded. Once the diffusivity of the sound field was adequate, an increasing number of microphones were installed in each room until the average sound pressure level, log averaged over all positions did not sufficiently change (maximum allowable deviations shown in Table 6.11 above).

Table 6.13 shows the average sound pressure for an increasing number of microphones installed in the receiving room. This shows that there was little difference between using five or six microphones, and therefore it was concluded that five microphones adequately sampled the sound field in each room. This number of microphones is in line with the requirements of ISO 10848-2.

Table 6.13: Average sound pressure level measured for one to six microphones located within the receiving room

Frequency, Hz	1 Microphone	2 Microphones	3 Microphones	4 Microphones	5 Microphones	6 Microphones
100	54.8	51.8	50.7	52.6	52.9	52.4
125	61.7	60.7	60.5	59.6	60.0	59.9
160	68.9	68.0	67.4	67.0	66.8	66.8
200	72.5	74.7	74.3	74.0	73.3	73.4
250	72.3	72.1	72.5	72.0	71.4	71.5
315	70.5	73.1	73.7	73.2	72.1	72.1
400	69.7	69.4	70.0	70.4	70.2	70.2
500	69.7	68.0	69.2	69.4	69.4	68.9
630	67.7	67.0	68.1	68.3	68.2	68.1
800	69.9	69.4	69.5	69.4	69.3	69.2
1000	65.5	66.5	66.6	66.3	66.1	66.1
1250	62.0	63.4	63.1	62.7	62.7	62.7
1600	62.8	63.6	63.6	63.4	63.4	63.4
2000	62.4	62.2	62.4	62.1	61.9	61.9
2500	59.3	59.1	60.1	59.9	59.5	59.5
3150	57.2	56.5	57.4	57.7	57.6	57.6
4000	53.8	53.4	54.2	54.1	53.9	53.9
5000	50.4	50.2	50.3	50.0	50.1	50.1

6.5.8 Flanking sound paths

To measure the flanking sound paths between the source and receiving rooms the sound pressure levels were measured in the receiving and source rooms simultaneously with a loudspeaker producing white noise in the source room. Sound pressure levels were used as this method measured the sound coming through all flanking paths.

A double stud wall was effectively created, with 13 mm Standard GIB plasterboard, 18 mm MDF, and 4 kg/m^2 mass-loaded barrier added to one side of the double stud wall, and with 18 mm plywood installed on the other side of the wall. 90 mm thick fibrous insulation was installed in the cavity. The plenum was then blocked up with three layers of 13 mm plasterboard in the grid space closest to the separating wall, with a single layer of 10 mm plasterboard ceiling tiles on the back two grid spaces. Two layers of 4 kg/m^2 mass loaded barrier were installed flat over the three layers of plasterboard ceiling tiles over the separating wall. A 4 kg/m^2 and a 6 kg/m^2 were hung like a curtain from the roof to the top of the mass loaded barrier on top of the plasterboard ceiling tiles. These curtains were sealed to the roof, sides, and suspended ceiling. Baffle stacks (fibrous batts, compressed by a minimum of 40 %) were installed on each side, over the mass loaded barrier on top of the plasterboard ceiling tiles, and compressed hard against the exterior walls of the plenum.

This was expected to give adequate sound reduction through the plenum to enable evaluation of all other sound paths

With the floor, wall, and roof constructions as described above, the TL measured through all flanking paths was less than that required to measure high CAC rated ceiling tiles. Table 6.14 shows the TL through all flanking sound paths measured using the sound pressure test method outlined in ASTM E336[79].

Table 6.14: Preliminary pressure-pressure measurements of all flanking sound paths in the CFN facility at the University of Canterbury

Frequency, Hz	Transmission Loss, dB
100	29.2
125	34.5
160	38.2
200	40.9
250	40.4
315	43.4
400	46.3
500	47.8
630	48.9
800	51.6
1000	52.6
1250	53.0
1600	57.1
2000	57.9
2500	59.5
3150	63.6
4000	62.9
5000	65.9
STC	50

The floor of the receiving room was then laid with carpet and the two side walls and rear wall were overlaid with two layers of 50 mm polyester absorption. Sound intensity tests were then undertaken in accordance with ASTM E2249-02 on the ceiling surface, capping, separating wall, and floor to identify the sound paths of concern. The results from these measurements are shown in Table 6.15 below.

Table 6.15: Sound intensity measurements of all sound flanking paths of the CFN facility at the University of Canterbury

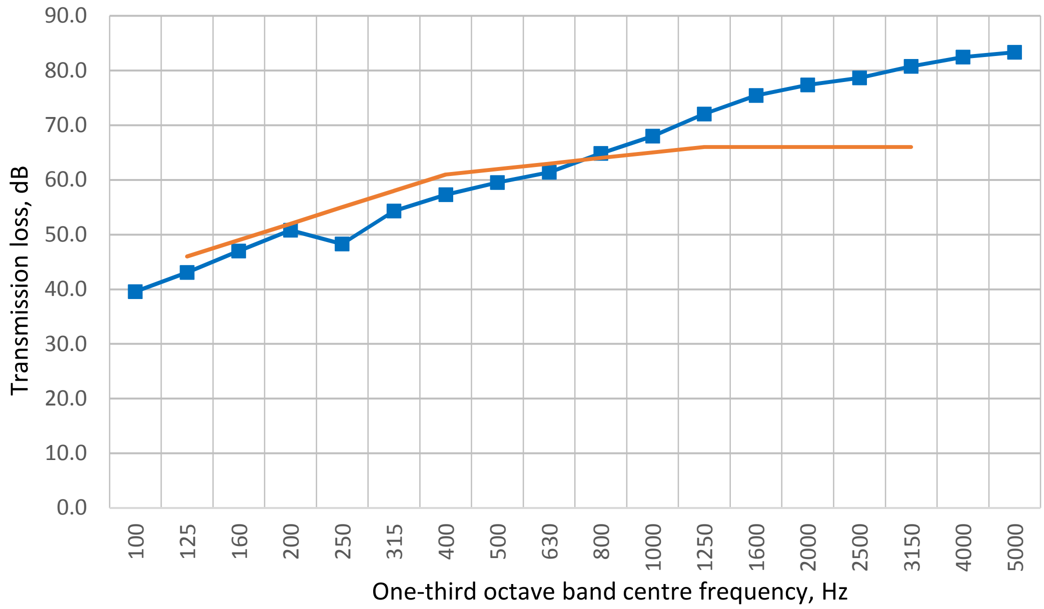
Frequency, Hz	TL of floor, dB	TL of $2m^2$ of separating wall, dB	TL of all separating wall, dB	TL of capping, dB	TL of external walls, dB
100	29.7	30.4	18.5	32.4	42.4
125	37.7	38.9	25.3	37.3	44.3
160	39.5	40.7	28.8	38.0	45.7
200	39.0	39.0	29.1	36.4	47.6
250	41.6	41.4	30.8	38.0	50.4
315	40.7	44.5	32.5	39.4	52.9
400	38.9	47.4	32.6	41.2	55.5
500	42.1	49.9	36.5	45.7	57.4
630	43.0	51.9	38.3	45.4	59.8
800	44.4	54.9	40.3	50.1	62.2
1000	42.5	57.1	40.1	51.7	58.6
1250	43.9	62.3	43.5	55.1	64.4
1600	47.9	64.0	47.7	59.7	67.8
2000	48.8	63.6	49.4	62.4	67.1
2500	48.1	66.2	50.6	63.3	70.5
3150	50.5	69.4	56.7	65.8	72.3
4000	50.2	69.5	60.8	68.0	75.3
5000	52.2	70.0	62.3	72.0	77.4
STC	45	52	47	50	61

The sound intensity measurements suggest that the primary flanking paths were through the floor, separating wall, and capping.

The measurements suggested that there was not full structural discontinuity between the rooms, which may have been due to installing the two rooms to close. To ensure that a higher level of vibration isolation was achieved, noise isolating GIB clips ST-001 were installed and two layers of 13 mm GIB Noiseline installed on the side that has the 18 mm plywood originally installed on it. The floor was upgraded with a layer of 10 mm Standard GIB and 21 mm particleboard added to both rooms, over the entire floor of the rooms. The capping had two layers of 4 kg/m^2 mass loaded barrier adhered to it, and acoustic mastic was used to seal up any holes that were formed between the walls, suspended ceiling, pilasters, and floor.

Following the upgrades, the measured sound levels that were transmitted through the external walls and plenum were lower than that through other sound paths described above, and were above the STC 60 separation that was required to be achieved.

Once these upgrades were completed, new TL tests were carried out using sound pressure to evaluate all the flanking paths. This evaluation indicated that all the sound flanking paths were above STC 60. Additional measurements were made over a three day period at different times of the days in different conditions, with different microphone and speaker placement to ensure that all measurements were above the STC 60 requirement. Graph 6.5 shows the average sound TL of all flanking paths of all 20 measurements undertaken, with Table 6.16 showing the tabulated sound TL at each one-third octave bands.



Graph 6.5: Average TL of all flanking noise paths measured over three different days in different environmental conditions

Table 6.16: Average, minimum, and maximum transmission loss of the flanking noise path between the source and receiving rooms

Frequency, Hz	Average TL for the separating wall, dB	Minimum measured TL in each one-third octave band, dB	Maximum measured TL in each one-third octave band, dB
100	39.5	37.2	44.6
125	43.1	40.0	45.8
160	47.0	43.3	49.3
200	50.8	50.1	52.5
250	48.3	47.0	51.7
315	54.3	52.1	56.7
400	57.3	55.1	58.9
500	59.5	58.0	64.5
630	61.4	59.8	65.2
800	64.8	63.4	69.3
1000	68.0	66.5	72.4
1250	72.1	70.6	76.5
1600	75.5	74.0	79.9
2000	77.4	75.9	81.8
2500	78.6	77.2	83.1
3150	80.7	79.3	85.2
4000	82.5	81.0	86.9
5000	83.4	81.9	87.8

Table 6.16 shows that the flanking sound paths achieve STC 60 or higher in all measurements. This average TL is considered the flanking noise limit of the CFN facility. All measurements conducted should be 10 dB or lower below this limit to ensure that noise from other paths do not affect the TL of the product being tested.

The external walls were evaluated separately to ensure that noise could not go between rooms through the external walls and by flanking through the structural discontinuity. Sound intensity was used to determine the transmission loss of the external walls. This technique showed that the side walls (the length of the facility) achieved an acoustic rating of STC 35, and the end walls (width of the facility) achieved an acoustic rating of STC 31. The end walls achieved a lower sound rating due to the access doors installed in these walls. The TL of each external wall is shown in Table 6.17. Due to the external side walls achieving an STC of 35, as well as being in the same plane, it is expected that the TL of the sound path between the source and receiving rooms, through the external walls would be in excess of STC 70.

Table 6.17: TL of all external walls of the CFN facility at the University of Canterbury

Frequency , Hz	Source room side wall TL, dB	Sound room end wall TL, dB	Source room side wall TL, dB	Receiving room side wall TL, dB	Receiving room end wall TL, dB	Receiving room side wall TL, dB
100	20.8	17.6	16.9	19.8	19.6	22.1
125	26.4	23.4	26.4	25.3	25.9	22.8
160	28.2	25.9	27.5	27.5	26.8	26.9
200	32.2	29.2	30.9	29.9	27.0	30.9
250	33.9	30.1	33.4	31.5	29.3	30.7
315	34.2	30.6	34.7	33.9	29.0	33.5
400	35.3	31.5	34.7	33.6	31.1	33.6
500	35.3	32.6	36.6	35.6	31.7	35.1
630	36.6	29.9	36.5	35.4	30.5	37.3
800	37.1	33.0	36.4	35.4	31.6	37.2
1000	35.1	32.6	35.5	34.4	31.4	34.9
1250	33.7	30.3	34.9	33.3	30.1	32.8
1600	34.2	30.3	35.0	34.5	30.2	33.7
2000	34.7	31.0	35.1	35.1	30.5	34.8
2500	35.7	33.5	36.6	36.9	32.9	36.9
3150	39.5	35.6	40.7	39.6	35.7	38.4
4000	41.4	38.1	44.9	42.3	36.7	42.6
5000	43.8	39.5	49.5	45.5	37.4	45.5
STC	36	32	36	36	32	35

6.5.9 Test signal

The test signal used in all tests was a random white noise, which has the same sound power at all one-third octave bands through the test spectrum (100 Hz to 5,000 Hz). The white noise was generated through a Bruel and Kjær PULSE multi-analyser front end system, which was connected to a Bruel and Kjær type 4292 Omni-directional speaker, driven by a Bruel and Kjær type 4292 amplifier.

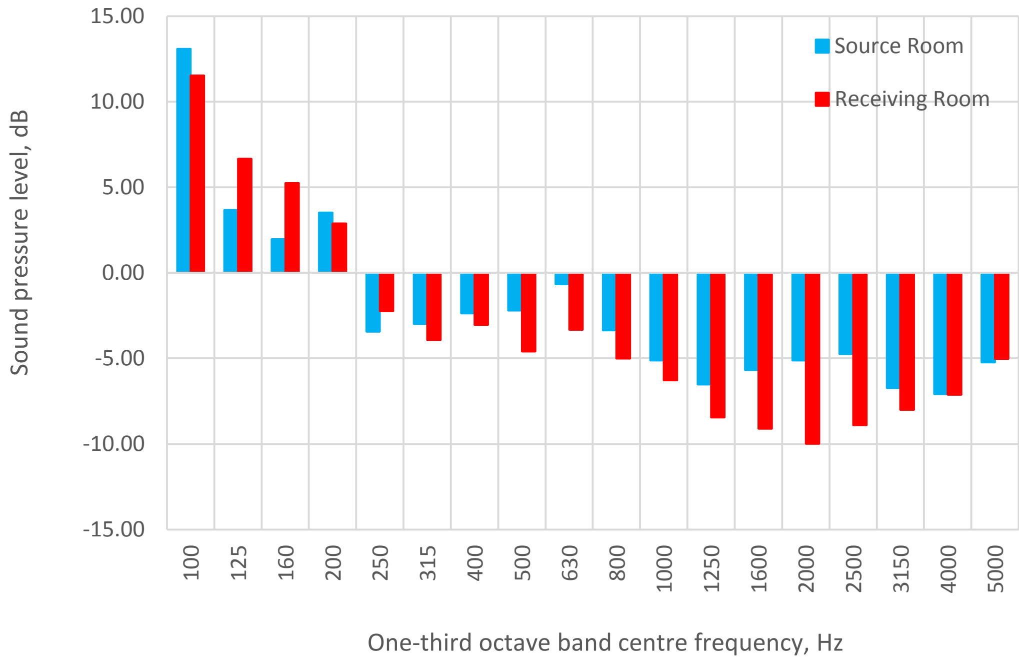
Before completion of each test, the background noise level in the receiving room was measured, to ensure that the background noise level was sufficiently low so to not influence the tests results. The measured background noise was also compared to the limits of the microphones used in the test to ensure that the inherent noise of each microphone was not being measured.

The test signal was generated for five seconds before the start of each test to ensure that the sound field in the source and receiving room is sufficiently excited. Ten microphones measured the sound field within the source and receiving rooms simultaneously for 30 seconds. The PLUSE system then turned the speaker off, one-half second after the 30 second measurement was completed.

The measured background noise levels were then compared to the test noise levels in the receiving room to ensure that the noise from the loudspeaker was 10 dB above the background noise level. If this was not the case, the sound power of the loudspeaker was increased such that it was 10 dB higher than the background noise level, and the test was repeated.

6.5.10 Background noise level

Background noise levels in the source and receiving rooms were measured using a single GRAS 40HF low noise microphone. Five different microphone positions were used in each room. Tests at each of the five positions were carried out on two different days (total of 10 measurements for both rooms). The average background noise level for each room is shown in Graph 6.6.



Graph 6.6: Average background noise levels measured in the source and receiving room using a low noise microphone

The product datasheets for the Bruel and Kjær 4189 ½ inch microphones that were used for standard plenum sound path measurements have a dynamic range between 14.6 dB and 146 dB, with an inherent noise floor of 14.6 dB. As the GRAS 40HF low noise microphones had a much lower noise floor, these were used for the background noise level measurements.

6.5.11 Suspended ceiling system installation

The suspended ceiling was installed as outlined in ASTM C636-13, as well as to AS/NZS 2785:2000 *Suspended ceilings – Design and installation*[80], where details were not given in the ASTM standard.

A USG Donn 36 mm Exposed Grid suspended grid system was installed in the CFN facility at University of Canterbury to comply with the requirements of ASTM C636. A main deep 'T' was used which has an exposed face of 24 mm and a height of 38 mm. The cross deep 'T' members had a 24 mm exposed face with a height of 35 mm. The main and cross 'T' members are constructed from double web roll formed hot dipped galvanised steel with galvanised painted steel capping over the exposed face.

When installing the USG suspended ceiling grid, the hangers that connect to the main 'T' runners are spaced 1200 mm apart, and are vertical hung a maximum of one-sixth out of direct vertical (angle of 15 degrees from vertical or less). The hangers were constructed of 12-gauge steel wire, which was fastened to the plywood roofing structure with timber anchors. The wire was attached to the main 'T' runners by wrapping it tightly through holes at 1200 mm centres and bending it sharply, such that there was no vertical or rotational movement of the main 'T' runner. The wire was then wrapped around itself three to five times within a 75 mm vertical length of the "T" member or top steel hanger at the bottom and top. The end of the wire was wrapped around itself, further with the end pointing vertically up, so that the ceiling tiles are not damaged, or were not a safety concern when installing ceiling tiles.

The cross 'T' members clipped into the main 'T' runners and are perpendicular to each other using the splines of the suspended ceiling grid. Where two cross 'T' members clipped into the same joint in the main 'T' runner, the splines interlocked sufficiently to create a fixed mechanical joint. The exposed bottom face of the cross 'T' member is partially recessed at each end, such that it overlaps the main 'T' runner. A cross-section through the main 'T' / cross 'T' member is shown in Figure 6.4.

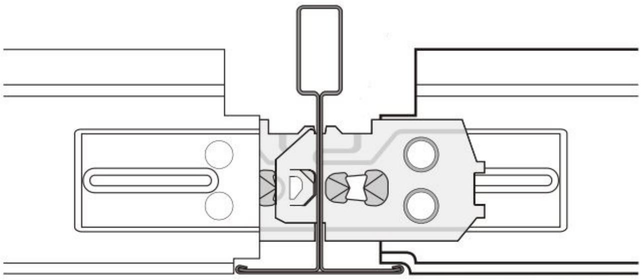


Figure 6.4: Section through the main 'T' runner and cross 'T' member showing the spline connecting two cross 'T' members, and the recessed edge of the cross 'T' members [81]

The suspended ceiling was designed such that a width 'T' was installed over the capping on top of the separating wall. This allowed easier installation of the ceiling tiles than trying to straddle a ceiling tile over the separating wall. The layout of the ceiling tiles, pilasters, and edge shelves is shown in Figure 6.5.

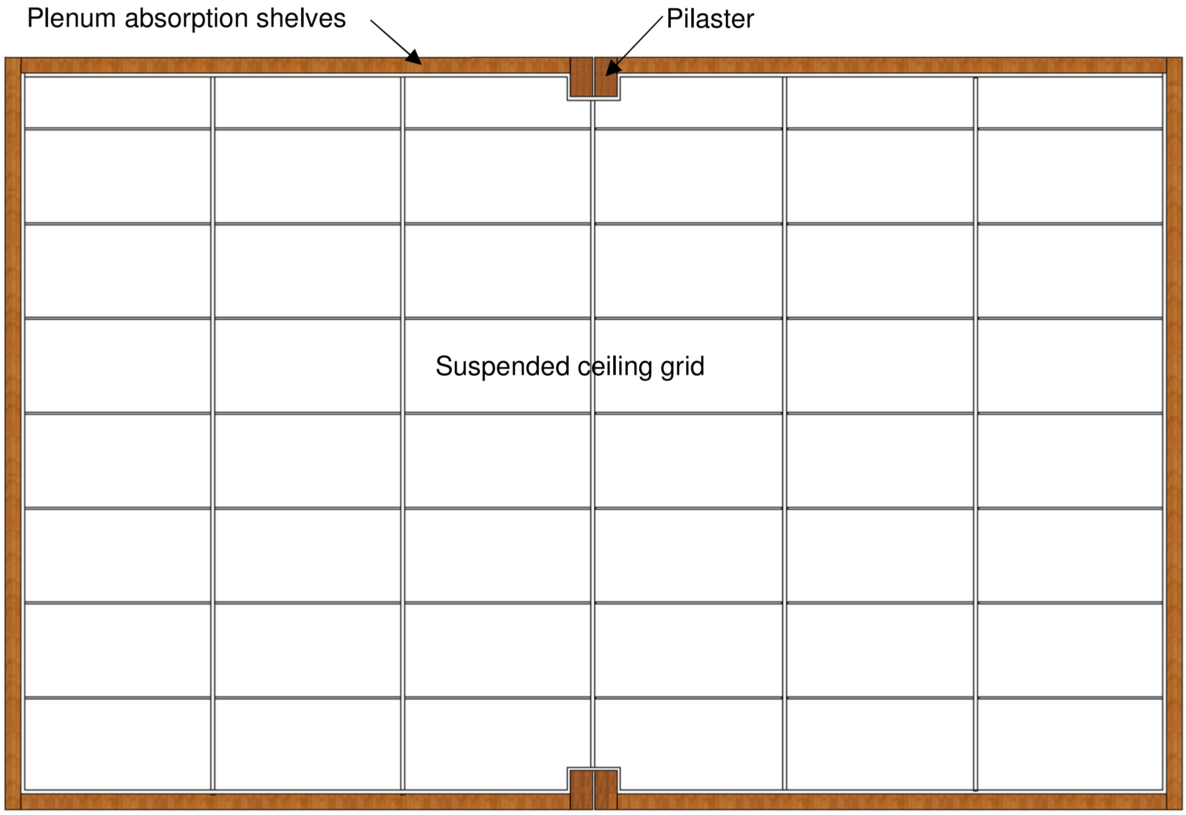


Figure 6.5: Layout of the suspended ceiling, pilasters, and edge shelves in the CFN facility at the University of Canterbury

6.5.12 Results

For each test undertaken, a report must be complied that complies with section 10 *Report* of ASTM E1414-11a, with relevant parts of ISO 10848-2 if additional information is required.

Each test is to be in direct accordance with ASTM E1414-11a, and noted in the report. A full description of the test specimen is to be included, including thickness, mounting conditions, front facing material, thickness, weight per square metre, and any other conditions of the tile that may affect the acoustical properties of the tile. Any additional plenum treatment must be included in the description that includes a plenum barrier, additional plenum absorption, ductwork and the like.

The suspension system is required to be identified by a three letter system, as described in section 6.3.12.

The normalised transmission loss at one-third octave bands of the test frequencies (100 Hz to 5,000 Hz), and overall CFN value is to be given, with a description of the source and receiving room (width, length, height, and volumes), as well as the internal environmental conditions (temperature, humidity, and pressure).

Finally a statement of the significance of the results, as well as the limitations must be given. The full one-page results report for each suspended ceiling system tested is given in Appendix A.X.

6.6 Comparison of previous CFN facility measurements

To ensure that the CFN facility had been accurately commissioned, tests were conducted on ceiling tile products that have previously been tested at other CFN facilities internationally.

ASTM E1414-11a recommends that two ceiling tiles are tested and compared to the repeatability and reproducibility limits outlined in the Standard. The first is to be a mineral fibre ceiling tile that is 16 mm thick and the second, a fibrous ceiling tile that is 25 mm thick. A 16 mm mineral fibre ceiling tile could not be sourced from any local supplier. The closest that could be sourced was a 15 mm mineral fibre ceiling tile, however this ceiling tile varied in thickness, as it had a square textured surface that varied the thickness by 5 mm so was considered unsuitable. A 25 mm fibrous ceiling tile could be sourced easily.

Data for a high CAC rated ceiling tile (AMF Thermatex Silence) was sourced from a local supplier, and this was substituted for the 16 mm fibrous ceiling tile. As the TL data was known for this ceiling tile and if similar results could be achieved using the CFN facility then this would suggest that the facility could accurately replicate measurements made at other CFN facilities.

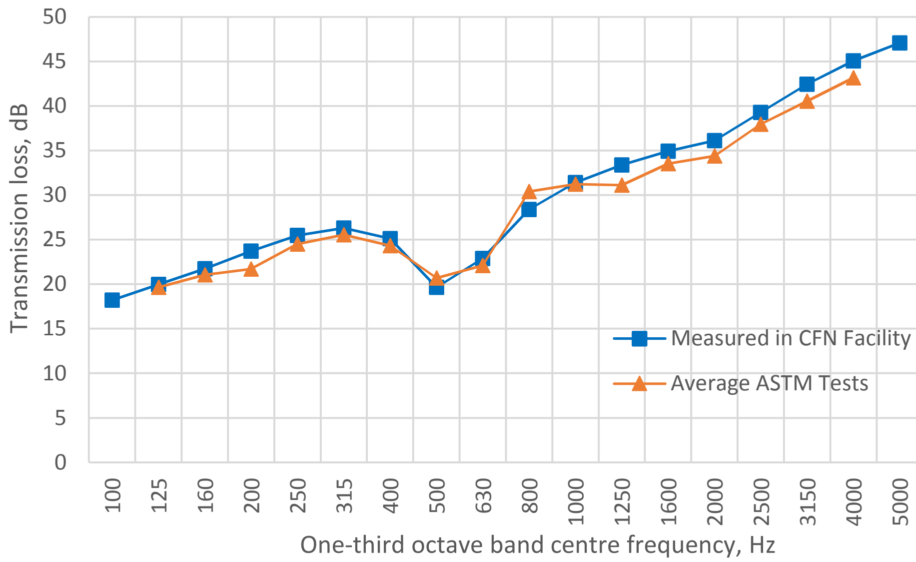
6.6.1 25 mm fibrous ceiling tile

To ensure that the CFN facility is properly commissioned, ASTM E1414-11a requires that a 25 mm fibrous ceiling tile is tested and is within the reproducibility limits outlined within the ASTM E1414-11a Standard, and reproduced in Table 6.4. In addition, when measuring the TL of these tiles in the same laboratory the results are required to be within the reproducibility limits set in the standard.

As described in Chapter 5, ceiling tile construction and properties can differ significantly between manufacturers, and therefore lead to varying TL data for essentially the same product. The manufacturer of the ceiling tiles is not specified in the ASTM E1414-11a Standard and so T&R Interior Systems CMax 25 mm fibrous ceiling tiles were used. These have a glass fibre facing installed, and are perimeter sealed with a light coat of plaster to all edges, and are shown in Figure 6.6.

Figure 6.6: 25 mm fibrous ceiling tile used for comparison test

Multiple different measurements were conducted using this ceiling tile over the course of a single day, with similar environmental conditions, and with the same person conducting the tests. The average TL from all five tests are shown in Graph 6.7. The TL outlined in ASTM E1414-11a for 25 mm fibrous tiles, the average TL of the 25 mm fibrous ceiling tiles measured, the difference between ASTM E1414-11a, and the average test results are shown in Table 6.18.



Graph 6.7: Average TL of 25 mm fibrous ceiling tiles installed within the CFN facility at the University of Canterbury

Table 6.18: TL results of the 25 mm fibrous ceiling tiles conducted at the CFN facility at the University of Canterbury compared to that outlined in ASTM E1414-11a

Frequency, Hz	Required TL in ASTM E1414-11a, dB	Average TL measured in the University of Canterbury CFN facility, dB	Difference, dB
125	19.64	19.96	0.32
160	21.04	21.72	0.68
200	21.71	23.72	2.01
250	24.48	25.47	0.98
315	25.54	26.32	0.78
400	24.32	25.12	0.80
500	20.69	19.66	1.03
630	22.11	22.87	0.76
800	30.39	28.39	2.00
1000	31.21	31.39	0.18
1250	31.10	33.39	2.29
1600	33.52	34.91	1.39
2000	34.70	36.12	1.72
2500	37.96	39.28	1.32
3150	40.54	42.43	1.89
4000	43.17	45.07	1.90

Table 6.18 shows that the 25 mm fibrous ceiling tiles tested in the CFN facility at the University of Canterbury are within the reproducibility limits outlined in ASTM E1414-11a (for the same

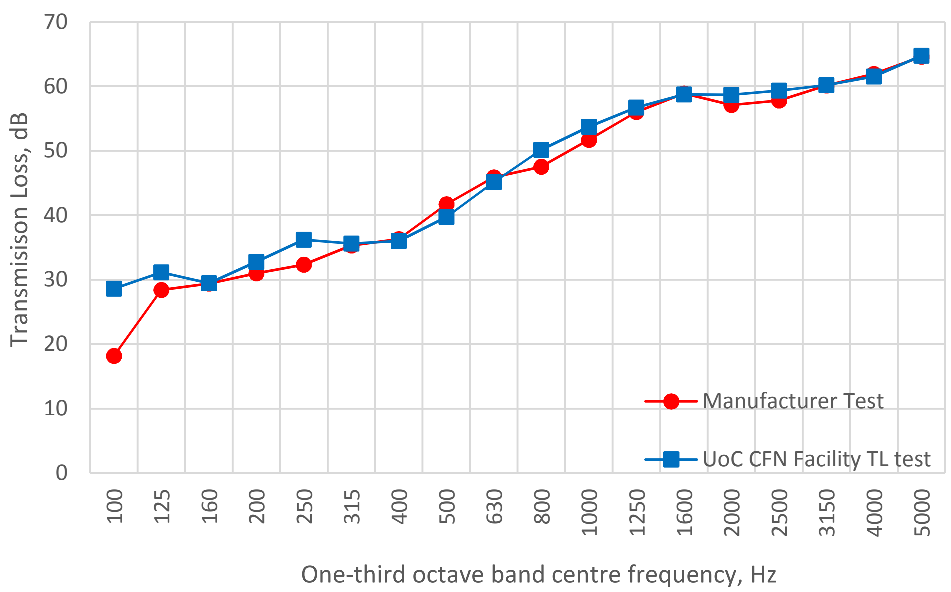
ceiling tile tested in different laboratories). The 25 mm fibrous ceiling tile was re-tested on the same day by the author (repeatability, as defined in ASTM E1414-11a).

From these measurements, it has been shown that the results for the 25 mm fibrous ceiling tile are within the limits outlined in ASTM E1414-11a, and it was therefore be considered that the facility is commissioned.

6.6.2 AMF Thermatex Silence

To ensure that the CFN facility is able to provide comparable results to other CFN facilities, AMF Thermatex Silence ceiling tiles were tested in the CFN facility, and compared to the manufacturer's published results. These tiles were tested in a laboratory in the United Kingdom, commissioned to ISO 10848-2:200. In addition to the difference in Standards, the ceiling tiles measured by the manufacturer were 600 mm x 600 mm where ceiling tiles tested in the University of Canterbury CFN facility were 1200 mm x 600 mm.

Graph 6.9 shows the TL of the AMF Thermatex Silence ceiling tiles tested in the University of Canterbury CFN facility (blue squares in Graph 6.9) compared to the manufacturer's data (red circles in Graph 6.8). While there is a difference the test results for the University of Canterbury CFN facility and by the manufacturers, these differences are put down to using different standards for conducting tests, and the different size of tiles.



Graph 6.8: TL results from AMF Thermatex Silence ceiling tiles when installed at the University of Canterbury CFN facility (blue square line) and when measured by the manufacturer (red circle line)

These results are comparable and (maximum deviation of 10 dB at 100 Hz, 3.8 dB at 250 Hz) when taking into consideration the two different test Standards, the ceiling tile dimensions, and that the results are largely within the reproducibility limits for the 16 mm mineral fibre ceiling tile outlined in ASTM E 1414-11a. The low frequency deviation could be explained due to the larger ceiling tiles used, or the additional absorption in the plenum (all perimeter walls covered, rather than three walls covered in the manufacturers test). This test data provides confidence that the CFN facility at the University of Canterbury has been commissioned accurately.

6.7 Summary

A CFN facility has been developed and commissioned at the University of Canterbury to meet the requirements of ASTM E1414-11a to carry out transmission loss measurements of a suspended ceiling between two adjacent rooms. Following a review of ASTM E1414-11a, a checklist was made, and each part was checked and tested to ensure that the requirements of the standard were satisfied. Preliminary measurements indicated the sound path through all paths apart from the plenum sound path and the average absorption of the surfaces below the suspended ceiling were did not meet the requirements of ASTM E1414-11a. Upgrades were made to the sound flanking paths of the separating wall and floor and additional treatment to the floor and walls allowed all requirements of ASTM E1414-11a are met.

Transmission loss measurements using the facility were conducted on a 25 mm fibrous ceiling tile, as described in ASTM E1414-11a, as well as a 42 mm mineral fibre ceiling tile, which had previously been tested. The 25 mm fibrous ceiling tile tests complied with the repeatability and reproducibility limits outlined within ASTM E1414-11a. In addition, the 42 mm mineral fibre ceiling tile was close to the TL of the manufacturer's test. Differences between the author's test and manufacturer's test were within the repeatability range given in ASTM E1414-11a. The CFN facility at the University of Canterbury was shown to comply with ASTM E1414-11a.

7.0 Measurements of Transmission Loss

7.1 Overview

The transmission loss (TL) of several different ceiling tiles and suspended ceiling systems were measured using the sound intensity method. The intensity method was preferred over the pressure-pressure sound level method as intensity is not influenced by external noise or flanking paths to the same extent as is the pressure-pressure method.

This chapter reviews the relevant standards, as well as the measurement methodology and calculations used to determine the TL of each product. TL measurements are presented in Chapter 8, and the results related to the CFN facility are given in Chapter 9.

7.2 Review of relevant standards

There are two international standards that describe how to conduct TL tests on products using the sound intensity method. These are ISO 15186-1:2000 and ASTM E2249-02. The ASTM standard was developed in North America and provides a measurement technique to calculate the TL of a product or partition system and to calculate a single number rating termed STC. The ISO standard, developed in Europe, provides a measurement technique to calculate the TL of a product or partition system to give a single number rating, R_w.

ISO 15186-1:2000 *Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity Part 1: Laboratory measurements*[65] was used to determine the TL of a ceiling tile and vertical suspended ceiling system. An intensity probe was used on the receiving room side of the product being tested with the sound pressure in the source room measured using an array of microphones. From this, the TL was determined for the single ceiling tile or suspended ceiling system in the 100 Hz to 5,000 Hz one-third octave bands.

7.2.1 Sound intensity

Sound intensity is a measure of the sound power per unit area (in W/m^2). For sound TL measurements, the sound intensity radiated from the receiving room side of the product is measured, and is space averaged over the area of the product being tested and time averaged over the time taken for the scan. The radiated sound power of the product under test can then be calculated.

Fahy[82, 83] details the application of sound intensity measurements, as well as the theory and calculation used to determine the sound intensity radiated by the product. The application of the theory is presented in these two texts and is only described briefly below for completeness.

The TL method of measuring intensity requires two phased matched microphones mounted a known distance apart. For all TL measurements in this research, a pair of Bruel & Kjær type 4189 ½-inch microphones, mounted 12 mm apart were used. The sound pressure half way between these microphones is then approximated from Fahy[82-83]. The sound pressure gradient between the two microphones is evaluated, which then allows the air particle velocity half way between the two microphones to be determined. The half-way sound pressure and sound pressure gradient equations can be combined to give an instantaneous intensity at a specific time and point[83]. The log time-averaged intensity measurements are averaged over the measurement area.

7.2.2 Requirements of the standard

ISO 15186-1:2000 requires two rooms (a source room, and a receiving room), that are open to each other through a reduced wall size opening (not the entire wall between the two rooms). All other sound paths between these rooms (apart from the opening) are required to reduce noise such that it is a minimum of 10 dB lower than that coming through the opening. For walls, the opening is required to be a minimum of 10 m^2.

The source room is required to be a room that has a minimum of volume 50 m^3 and has diffusing elements installed so that it is sufficiently diffuse (that is the TL results do not change with the addition of extra diffusing panels). The reverberation time of the source room is required to be between 1 and 2 seconds for frequencies at and above 100 Hz, or measured to ensure that the reverberation time does not affect the TL of the product.

The receiving room is required to be sufficiently sound absorbing such that the room meets the field indicator requirements of the ISO 15186-1:2000 standard. There are two field indicators. The first indicator is called the *Pressure-Intensity* (PI) *index*. This requires that the sound reflected in the room (i.e. the sound pressure within the room) is less than 10 dB of the sound power radiated from the product (intensity). Additional absorption is added to each surface of the receiving room (apart from the product being tested) until this can be achieved.

The second field indicator is called the *repeatability index*. This requires that two scans, one vertical and one horizontal scan that are within 1 dB of each other. The scan speed is required to be between 0.1 ms^{-1} to 0.3 ms^{-1} throughout the entire scan.

The laboratory for these measurements is required to have a background noise level and all flanking noise a minimum of 10 dB below the sound intensity level radiating from the product being tested. Both TL facilities at the University of Canterbury meet this criteria.

7.3 Measurement facilities

The TL measurements were conducted using the reverberation room and either of the semi-anechoic rooms at the University of Canterbury. The smaller semi-anechoic room was used to test the TL of a single ceiling tile and a small vertical suspended ceiling system, and the larger semi-anechoic room to test the TL of a large suspended ceiling system.

Previous work has been carried out to ensure compliance with the ISO 15186 and ISO 10140 suite of standards. This included changing the number of microphones and using different speaker locations[66]. This previous work identified suitable microphone and speaker positions in the source room. These microphone and speaker locations were used in all tests and are shown in Figure 7.1.

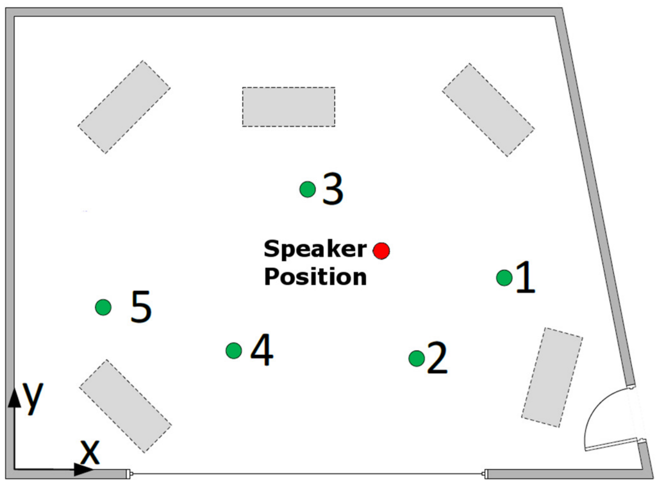


Figure 7.1: Location of microphones and speakers within the reverberation room at the University of Canterbury for transmission loss measurements

The TL tests were conducted on five different ceiling tile products, four made from mineral fibre (three had tissue facings and one had a painted and indented facing), with one being a composite ceiling tile. The ceiling tiles ranged in thickness and density to ensure that trends could be observed with different material properties. The vertical suspended ceiling grid used in either of the large or small TL facilities was the same for all the ceiling tile products tested. All the ceiling tiles were clipped into place using standard industry grid clips that are used to hold ceiling tiles in place during an earthquake event.

Research previously conducted using these two TL facilities has shown that testing the TL of a homogeneous material in the small TL facility gives slightly higher TL results than that tested in the large TL facility due to the difference in sample size[84].

7.3.1 Small transmission loss facility

The small TL facility utilises a doorway between the reverberation room and a small semi-anechoic room. The door accommodates a sample size of 1550 mm x 950 mm. This TL facility allows a quick and easy comparison between products with less materials than a full scale test.

The small semi-anechoic room has a total volume of 9 m^3, and a total surface area of 26.4 m^2. The room is lined on all walls with highly absorptive product, with the ceiling similarly lined, and a with deep pile carpet on the floor. The reverberation room is the same as that used for absorption coefficient measurements described in Chapter 3.0. A diagram of the reverberation room and associated small semi-anechoic room are shown in Figure 7.2.

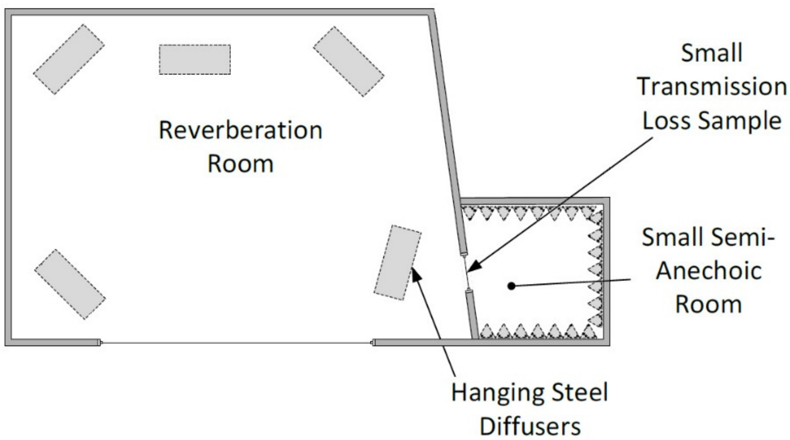


Figure 7.2: Reverberation room and small semi-anechoic room dimensions

The majority of ceiling tiles installed in offices and schools in New Zealand are 1200 mm x 600 mm. There are other sizes than these, but their use is unusual. ISO 15186-2:2000 allows the testing of small building elements so testing a single ceiling tile would fall within its scope. ISO 15186-1:2000 requires that the conditions outlined in ISO 140-10:1991 *Acoustics – Measurement of sound insulation in buildings and of building elements – Part 10: Laboratory measurement of airborne sound insulation of small building elements*[85] are met.

It is noted that ISO 140-10:1991 has been replaced by ISO 10140-1:2010 *Acoustics – Laboratory measurement of sound insulation of building elements – Part 1: Application rules for specific products*[86]. Annex E of this later version of the standard relates to small technical elements that are less than 1 m^2 in size (a single ceiling tile is 0.72 m^2). This standard has the same requirements as those of ISO 140-10:1995.

Using these standards allows the TL of a single ceiling tile to be tested in direct accordance with ISO 15186-1:2000. For a vertically mounted suspended ceiling system using the small TL facility, the tests will only be in general accordance with ISO 15186-1:2000, due to the small sample size.

7.3.2 Large transmission loss facility

The TL of a vertically mounted suspended ceiling system was tested using the University of Canterbury's large TL facility. The large TL facility utilises an opening in a wall between the reverberation room and a large semi-anechoic room. The large TL test opening has internal dimensions of 4200 mm x 2400 mm. This size of opening allows for measurements to be conducted in direct accordance with ISO 15186-1:2000.

The large semi-anechoic room has a volume of 200 m^3, and a surface area of 236 m^2. All the walls and roof are lined with highly sound absorptive lining, with hanging absorbers located in line with the opening, which results in an absorptive 'tunnel'. The floor is lined with a deep pile carpet, and additional sound absorption panels are laid on the floor. A sketch of the reverberation room and large semi-anechoic room is shown in Figure 7.3.

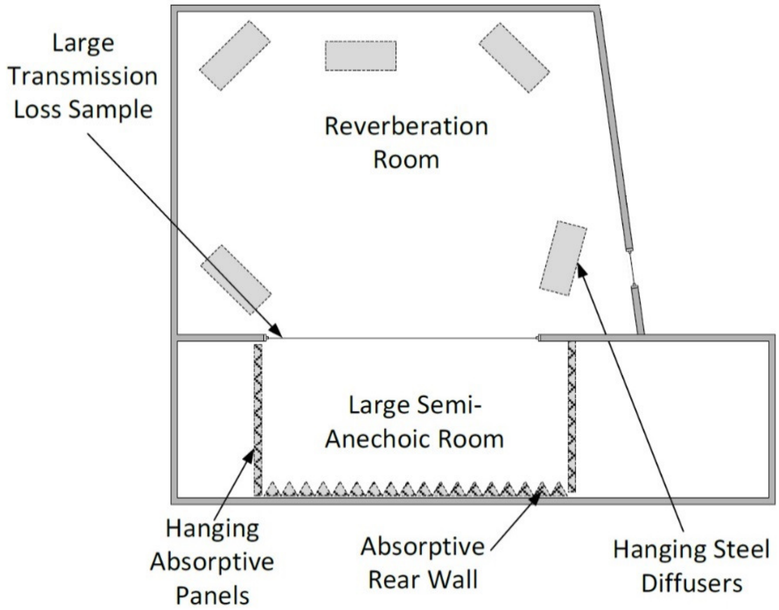


Figure 7.3: Reverberation room and large semi-anechoic room dimensions

As the suspended ceiling did not fall under the category of 'wall' or 'floor' as outlined in ISO 15186 - 1:2000, the minimum area of 10 m² was not applicable. A reduced area of approximately 5.8 m² was used, that allowed a two ceiling tile high by four ceiling tile wide vertical suspended ceiling grid to be constructed. This gave a sufficient area of suspended ceiling and ceiling tiles to allow accurate measurements of the leakage from the suspended ceiling system.

The conditions of ISO 140-10:1991 and ISO 10140-1:2010 were followed where appropriate for these tests which allowed measurements in direct accordance with ISO 15186-1:2000.

7.4 Transmission loss measurement procedure

The determination of the TL of a single ceiling tile and a vertically mounted suspended ceiling system were completed in accordance with ISO 15186-1:2000, and described below. The TL of each ceiling tile and suspended ceiling system were determined by measuring the sound pressure in the source room and the sound power radiated by the product being tested in the receiving room. The intensity sound power radiated by the product or system was measured using a Bruel and Kjær 2863 intensity probe attached to a 2260 Bruel & Kjær handheld sound level meter.

Firstly, five Bruel and Kjær type 4189 free field microphones were arranged in the standardised test locations in the reverberation room. A Bruel and Kjær 4292-L dodecahedron speaker sound source was also placed in the reverberation room, at the required standardised point. These standardised points comply with ISO 15186-1:2000, ISO 140-1:1997, and ISO 140-3 1991, being 0.7 metres from any other microphone the room boundaries and diffusers, and 1 metre from the test element and speaker. The relative positions of the microphones and speaker are shown in Figure 7.1.

The source room microphones and the intensity probe were calibrated before each test using a Bruel and Kjær 4321 calibration meter. The associated microphone coupler was used when calibrating the intensity probe.

One of two test installation procedures were followed depending on which TL facility was being used, and are described in sections 7.4.1 and 7.4.2. The test procedure that was followed using either of the TL facilities was:

> Once the microphones were calibrated and the ceiling tile or suspended ceiling system were installed in the associated TL facility, the background noise level was measured for 30 seconds. The sound source was then turned on to a volume such that it was a minimum of 10 dB over the background noise level in the receiving room. Each of the five microphones in the source room measured the sound pressure level in the reverberation room for 30 seconds.
>
> While the speaker was still on, the intensity level was measured using the Bruel and Kjær type 2683 intensity probe attached to a handheld Bruel and Kjær 2260 sound level meter. A vertical and horizontal scan was performed across the surface of the ceiling tile or suspended ceiling system, of the semi-anechoic receiving room side, at approximately 150 mm from the surface of the test product, as shown in Figure 7.4.

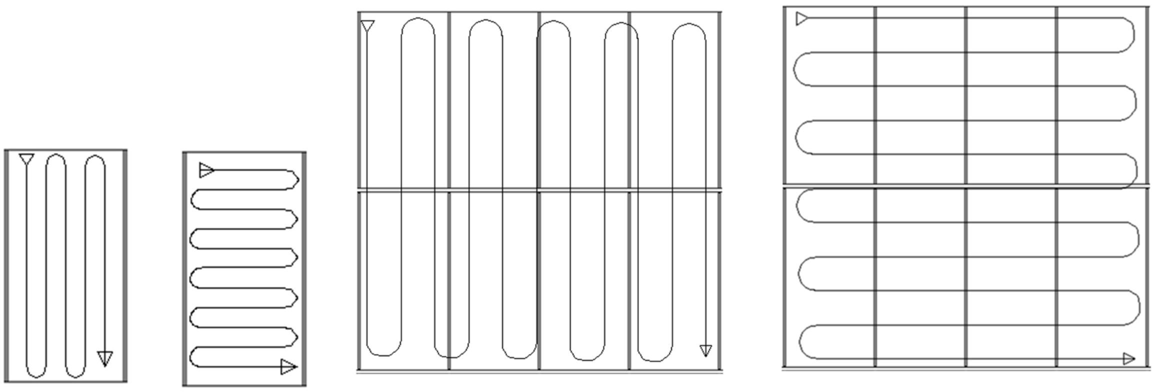


Figure 7.4: Scan diagram used for small (left) and large (right) transmission loss tests

The PI index for the scans was calculated and the repeatability index evaluated. If the PI index was higher than 10 dB or the repeatability index higher than 1 dB at any single one-third octave band frequency between 100 Hz and 5,000 Hz, the tests were repeated. Three pairs of scans were completed for each ceiling tile or suspended ceiling system (total of six individual scans).

The TL was then calculated using the process and equations outlined in section 7.4.3

7.4.1 Construction and installation of the test specimen in the small TL facility

The small TL facility was used to measure the direct sound transmission through a ceiling tile and also through a small suspended ceiling grid, that one full ceiling tile could be installed in.

To determine the TL of a single ceiling tile, a full sized ceiling tile and off-cuts to fill the entire frame were sandwiched between two sheets of 18 mm MDF, with an opening in each side. This sandwich system was installed in the test aperture in the small TL facility, and 20 mm x 20 mm rectangular steel sections were installed around the perimeter of the frame. Fourteen M8 bolts, torqued to 2 Nm, were installed around the perimeter compressing the steel into the partition and holding the test product in place.

To determine the TL of a small suspended ceiling grid a 30 mm wide timber frame was constructed 2 mm smaller than the test aperture on each side. A small suspended ceiling was installed in this timber frame so one full ceiling tile could be installed in the middle, with filler ceiling tiles of the same product installed around the perimeter. The ceiling tiles were held to the frame using seismic clips which apply pressure to the back of the ceiling tile, shown in Figure 7.5. These are typically used for stopping ceiling tiles popping out during earthquakes.

Figure 7.5: Suspended ceiling grid with ceiling tiles installed in the large TL facility at the University of Canterbury

The aluminium 'L' angle around the perimeter of the suspended ceiling were screwed into a timber frame, as would typically be constructed around the perimeter of a suspended ceiling. 20 mm x 20 mm rectangular steel sections were installed around the perimeter of the timber frame and fourteen M8 bolts, torqued to 2 Nm, were installed around the perimeter compressing the steel into the partition and this holds the test product in place. Figure 7.6 shows the small suspended ceiling grid with ceiling tiles installed in the small TL facility.

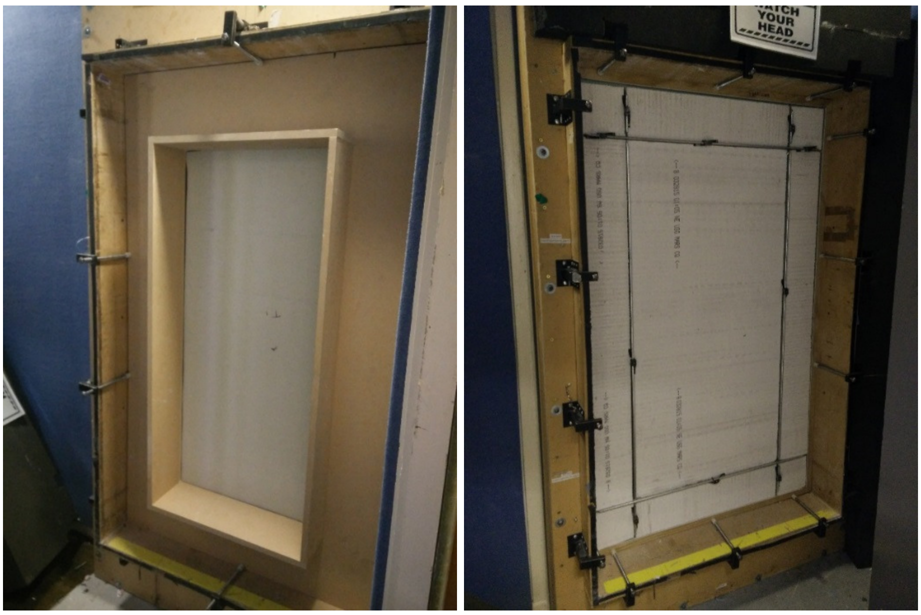


Figure 7.6: Single ceiling tile (left), and small suspended ceiling grid (right) with ceiling tiles installed within the small TL facility at the University of Canterbury

Once the product was installed in the small TL facility, the TL was measured as described above.

7.4.2 Construction and installation of the test specimen in the large TL facility

Eight full size ceiling tiles were installed in a suspended ceiling grid in the large TL facility at the University of Canterbury.

The large suspended ceiling grid was installed in the opening between the reverberation room and the large semi-anechoic room. An aluminium 'L' angle around the entire perimeter was screwed into a timber surround that was bolted into the concrete frame of the opening. A typical two high by four wide ceiling tile suspended ceiling grid was installed in the opening so that the suspended ceiling grid was vertical between the rooms.

Ceiling tiles were then installed in the suspended ceiling grid, seismic clips were used to maintain a tight fit between the ceiling tile and grid. Figure 7.7 shows the suspended ceiling grid with ceiling tiles installed within the grid, when looking from the reverberation room. Figure 7.5 details the seismic clips installed on a suspended ceiling system that were used to hold the ceiling tile in the vertical suspended ceiling grid.

Figure 7.7: Suspended ceiling grid with ceiling tiles installed in the large TL facility at the University of Canterbury

Once the ceiling tiles were installed in the suspended ceiling grid in the large TL facility, the TL was measured as described above.

7.4.3 Calculation of the transmission loss

Once the PI index and repeatability index were assessed (using the equations and parameters described below), and found to be acceptable, the TL of each product was then calculated from the measured sound pressure level in the source room and sound intensity measurements in the receiving room.

The PI index is the difference between the sound pressure level and the measured sound intensity level of the product. This is required to be below 10 dB during the tests. To calculate the PI index (F_{pI}), the sound intensity measured (L_{In}) is subtracted from the sound pressure level (L_p) at all one-third octave bands, as given in Equation 7.1.

$$F_{pI} = L_p - L_{In} \qquad \text{Equation 7.1}$$

The repeatability index is the difference between the measured intensity during the vertical and horizontal scans. This is required to be below 1 dB in all one-third octave bands. The repeatability index (R_i) is calculated by subtracting the sound intensity measured in the horizontal direction (L_h) from the sound intensity measured in the vertical direction (L_v), as given in Equation 7.2.

$$R_i = L_v - L_h \qquad \text{Equation 7.2}$$

If the requirements of the PI index and repeatability are met, then the intensity TL can then be calculated from the tests. ISO 15186-1:2000 details the calculation of the TL using the measured sound pressure level in the source room, and the measured sound intensity level, reproduced in Equation 7.3 below.

$$R_i = L_{p1} - 6 - \left[L_{In} + 10\log_{10}\left(\frac{S_m}{S}\right)\right] \qquad \text{Equation 7.3}$$

Where R_i is the intensity sound reduction index, L_{p1} is the average sound pressure level measured over the five microphones located within the reverberation room, L_{In} is the average sound intensity level measured over the product in both the vertical and horizontal direction over the three measurements taken, S_m is the total surface area of the product, and S is the area of the test specimen that was scanned.

If the area of the product is equal to the area that was scanned with the intensity probe (i.e. S_m = S), then Equation 7.3 can be refined to:

$$R_i = L_{p1} - 6 - L_{In} \qquad \text{Equation 7.4}$$

The equations were used to determine the TL at each one-third octave band between 100 Hz and 5,000 Hz for all single ceiling tiles and suspended ceiling systems. Once the TL in the one-third octave bands was calculated, the TL was fitted to the STC or R_w standardised curves, and the single number rating was determined.

7.5 CFN facility measurement procedure

The CFN facility was used to determine the Tl through the plenum sound path. The ceiling tile products tested were the same as that tested in the vertical suspended ceiling system. The Armstrong Ultima ceiling tiles were not tested. All tests were carried out in direct accordance with ASTM E1414-11a, with the entire ceiling installed with the ceiling tile product. The same USG Donn suspended ceiling grid system was used for the suspended ceiling in the CFN facility to the TL facilities, with the same “T” dimensions.

To determine the TL through the suspended ceiling grid, the entire suspended ceiling grid through the CFN facility (shown in Figure 6.5) has the same product of ceiling tiles installed in it. There were a total of 48 ceiling tiles (42 full ceiling tiles and 6 half tiles). Gravity held the ceiling tiles in the grid.

Once the ceiling tiles were installed (or absorption laid on the rear side of the plenum), the following methodology was used to determine the TL through the plenum sound path

> Five microphones were placed in the determined positions in each of the source and receiving rooms. The loudspeaker was placed in the source room in a predefined location. All microphones were then calibrated.

Once the microphones were calibrated, the background noise level is measured for 30 seconds. The sound source was then turned on to a volume such that it is a minimum of 10 dB over the background noise level in the receiving room. This was played for five seconds before the microphones started recording.

Each of the five microphones in the source and receiving room measured the sound pressure level for 30 seconds. The microphones automatically stopped measuring after 30 seconds, and the loudspeaker played for a half second after the microphones stopped recording and turned off after this.

The environmental conditions in both rooms were measured to ensure they were comparable. The reverberation time in the receiving room was then measured using the decay method. The loudspeaker played a random noise for 7 seconds and then was shut off. Five microphones measured the T_{20} and T_{30} and a T_{60} was extrapolated from the measurements. Using the environmental conditions and reverberation time, the decay rate in the receiving room was determined. The TL through the plenum sound path, taking into consideration the absorption in the receiving room was then calculated using the following equation:

$$D_{n,c} = L_1 - L_2 + 10\log\left({}^{A_o}/_{A}\right) \qquad \text{Equation 7.5}$$

Where $D_{n,c}$ is the normalised ceiling attenuation, in dB, L_1 is the average one-third octave band sound pressure level in the source room, in dB. L_2 is the average one-third octave band sound pressure level in the receiving room in dB. Ao is 129 Sabin (12 m^2), and A is the sound absorption of the receiving room in Sabin (m^2) measured using the decay method.

7.6 Summary

Sound intensity was used to determine the TL of single samples of ceiling tiles and two suspended ceiling grids. These tests were carried out in direct accordance with ISO 15186-1:2000 as well as other relevant standards relating to small building elements.

The TL of four different mineral fibre ceiling tile products and one composite ceiling tile product was measured when installed, in a small and a large TL suspended ceiling grid. Each ceiling tile product was manufactured by a different organisation and had different material properties.

The intensity technique was used to measure the TL of the single ceiling tile and the suspended ceiling systems in both TL facilities. Sound intensity was utilised as it reduced any unwanted flanking noise. Two different TL facilities were used, a small TL facility to measure just the TL of a ceiling tile, and a small suspended ceiling grid, and a large TL facility to measure the TL of a larger suspended ceiling grid.

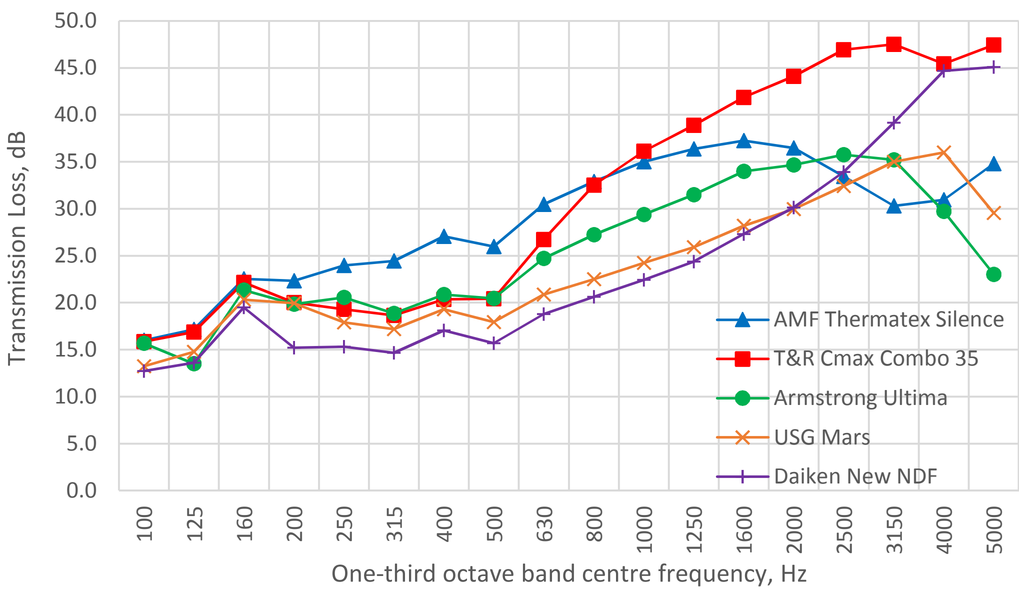
8.0 Transmission Loss Results

8.1 Overview

The transmission loss (TL) results for a single tile, through a small suspended ceiling system, and through a large vertical suspended ceiling system are presented in this chapter. The results for the single ceiling tile were compared to that for a suspended ceiling system to determine the effect of the grid on the Tl of the suspended ceiling system. The small and large suspended ceiling grid results were also compared to determine what effect the grid size had on the TL. The complete set of measurements are given in Appendix A.X.

8.2 Ceiling tile measurements

The results for just a single ceiling tile is shown in Graph 8.1. All single ceiling tile measurements showed a general similarity with a low frequency region where the TL does not increase significantly (between 100 Hz and 500 Hz). After this region, the TL increases with frequency (approximately 3 dB per one-third octave band) between 500 Hz and approximately 2,000 Hz. Above 2,000 Hz the drop in TL is probably due to the coincidence dip of the ceiling tile which is controlled by the mass and stiffness of the panel. The heavier tiles have a coincidence region at a lower frequency, for example the Daiken New NDF probably has a coincidence region at a frequency in excess of 5,000 Hz.



Graph 8.1: Transmission loss of a single ceiling tile

The TL curves generally increase with the mass of the tile. The Daiken New NDF ceiling tile was the thinnest ceiling tile tested (12 mm), and had the lowest surface mass (3.3 kg/m^2), which resulted in the ceiling tile having the lowest TL. The TL above 2,000 Hz of the Daiken New NDF ceiling tile continues to rise when compared to other ceiling tile products because the critical frequency is likely to be much higher than for the other tiles.

The TL between 160 Hz and 800 Hz, of the AMF Thermatex Silence ceiling tiles increases, rather than staying relatively constant. The TL increases at a higher rate above 800 Hz until 1,600 Hz, where the TL curve starts to decrease to approximately 30 dB at 3,150 Hz. The coincidence region starts at a lower frequency compared to other ceiling tiles as this is the heaviest ceiling tile (10.8 kg/m^2).

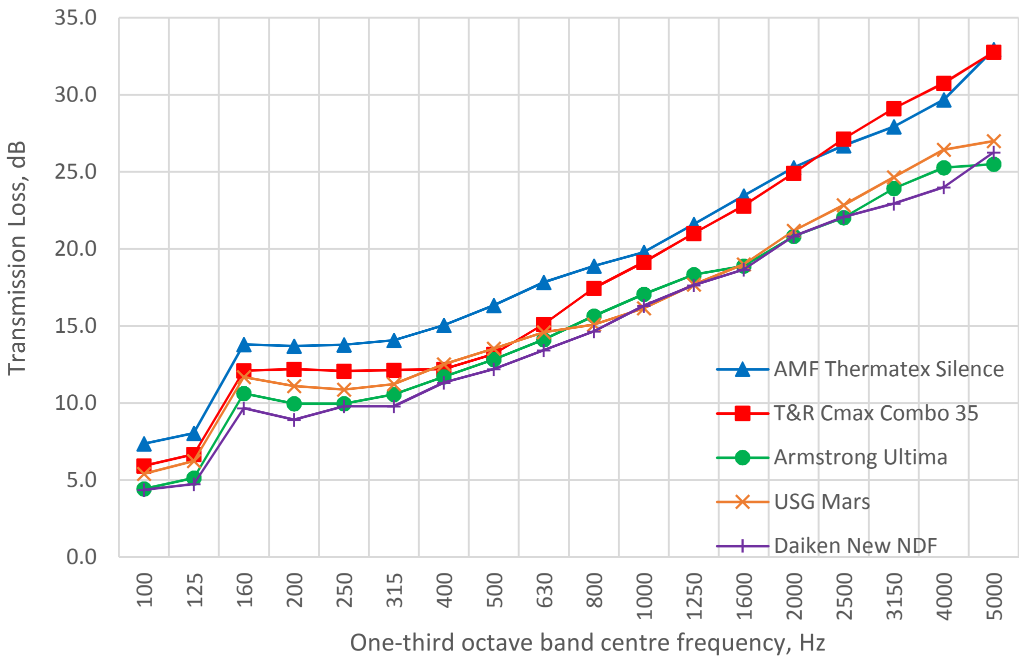
The low frequency TL region between 100 Hz and 160 Hz of the T&R Interior Systems CMax Combo 35 ceiling tile is similar to that of the other ceiling tiles measured. Between 100 Hz and 500 Hz, the TL of this ceiling tile is comparable to the TL of standard plasterboard[87, 88, 89] that suggests the 25 mm fibrous facing does not contribute to the TL at low frequencies. Above 500 Hz, the TL increases at approximately 3.5 dB per one-third octave, that may indicate that the glass fibre porous facing may increase the TL at higher frequencies. The coincidence region is in similar frequency bands to typical 10 mm plasterboard, however the coincidence dip is less, which may be due to the mounting conditions.

All products exhibit a similar increase in the 160 Hz frequency band, a characteristic of the TL facility. This has been seen in other TL tests completed using the facility [66, 84].

8.3 Small suspended ceiling measurements

The TL of the same five ceiling tiles mounted in a small suspended ceiling grid (Figure 8.1) are shown in Graph 8.2.

Figure 8.1: Small suspended ceiling installed between the reverberation room and the small semi-anechoic room without any ceiling tiles installed



Graph 8.2: Transmission loss of a small suspended ceiling system installed in the small TL facility

The TL measured in the small suspended ceiling system show that the TL steadily increases with increasing frequency, at a rate of approximately 1.3 dB per one-third octave band increase.

The results show that the higher the surface density of the ceiling tile gives a higher the overall TL. This is shown the most clearly between the Daiken New NDF (purple '+' in Graph 8.2), having a surface density of 3.3 kg/m^2, which compared to the AMF Thermatex Silence (blue triangles in Graph 8.2), having a surface density of 10.8 kg/m^2.

Overall, the TL of the T&R CMax Combo 35 ceiling tile increases at a higher rate than any of the mineral fibre ceiling tile products tested in this research (1.7 dB per one-third octave band compared to 1.3 dB for mineral fibre ceiling tiles). This was attributed to the plasterboard on the back face which had a higher surface density than the mineral fibre.

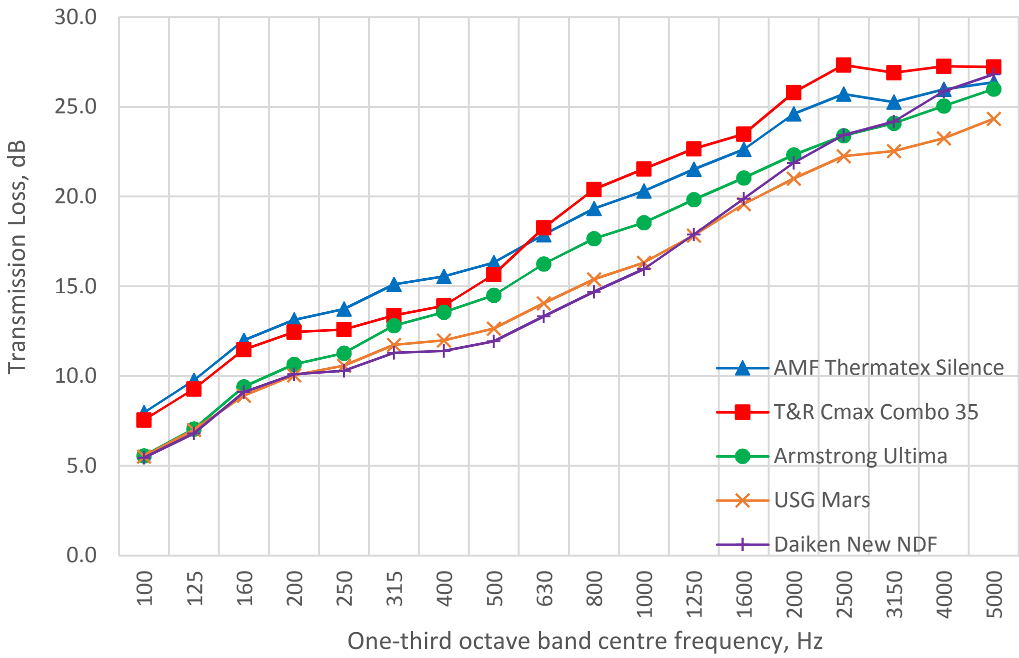
Leakage due to the suspended ceiling grid is discussed in section 8.5.1.

8.4 Large suspended ceiling measurements

The TL of the same ceiling tile products was measured in a larger suspended ceiling grid. The same type of suspended ceiling system used for the small suspended ceiling grid product was used in the large suspended ceiling grid (USG Donn system).

The ceiling tile products were installed in a large vertical suspended ceiling grid shown in Figure 8.2. The results from these measurement are shown in Graph 8.3.

Figure 8.2: Large suspended ceiling installed within the test face, looking from the reverberation room



Graph 8.3: Transmission loss of a large suspended ceiling system installed in the large TL facility

These results produce very similar results to those obtained in the small suspended ceiling grid. All results show a very similar TL curve, with the TL increasing at a steady rate of 1.2 dB per one-third octave band frequency increase. The peak at 160 Hz, is not seen in these measurements, which is probably a characteristic of the small TL facility.

The mass of the ceiling tile is the main determining factor of the TL. As the surface mass of the ceiling tile increases, the overall TL increases. The Daiken New NDF (surface mass of 3.3 kg/m^2), has the lowest TL curve (apart from the high frequencies (above 2,000 Hz), with the AMF Thermatex Silence ceiling tile (10.8 kg/m^2) having the largest TL.

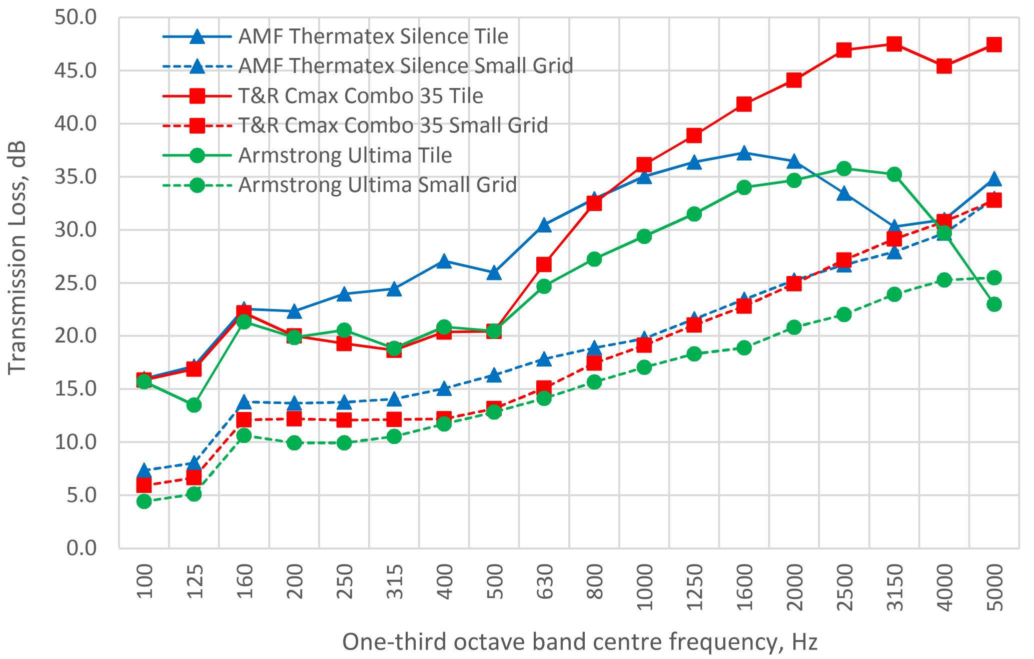
As seen in the small TL facility, the TL of the T&R Interior Systems CMax Combo 35 ceiling tile increases at a higher rate than the other ceiling tiles tested in the large TL facility.

8.5 Leakage of suspended ceiling grid

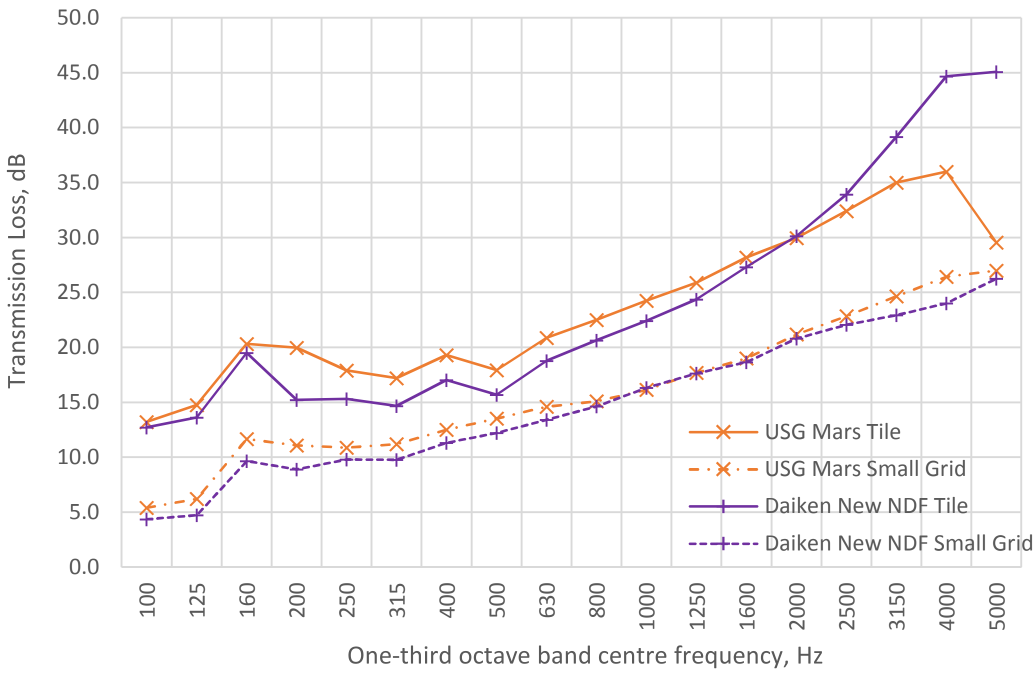
8.5.1 Leakage of a small suspended ceiling grid

A single ceiling tile can be considered as a single panel partition. However, when a tile is installed in a grid, leakage is likely occur through the grid.

Graph 8.4a and Graph 8.4b show the results from the TL test through ceiling tile products (solid line) and the ceiling tiles installed in a suspended ceiling grid (small dashed line). Both results were undertaken in the small TL facility.



Graph 8.4a: TL of a single ceiling tile (solid line) and the tile in a small suspended ceiling grid (dashed line) in the small TL facility



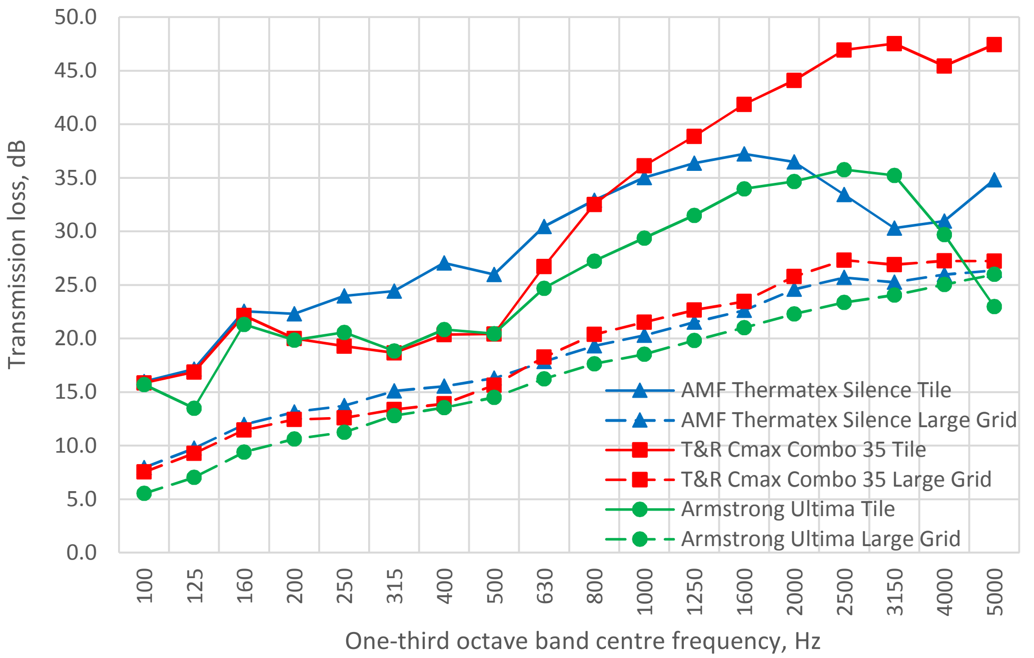
Graph 8.4b: TL of a single ceiling tile (solid line) and the tile in a small suspended ceiling grid (dashed line) in the small TL facility

The results show that the TL is higher of the ceiling tile alone without the presence of a grid, which was expected, as there is probably no sound leakage in the presence of the grid. The mineral fibre ceiling tiles exhibited on average, a 9.5 dB decrease in TL over the 100 Hz to 5,000 Hz frequency range when installed in a suspended ceiling grid. The composite ceiling tile exhibited a larger difference, with a decrease of, on average, 13 dB over the 100 Hz to 5,000 Hz frequency range when installed within a suspended ceiling system. For all tiles the decrease in TL ranged from almost 0 dB (at the coincidence region), to over 15 dB, at the end of the mass controlled region.

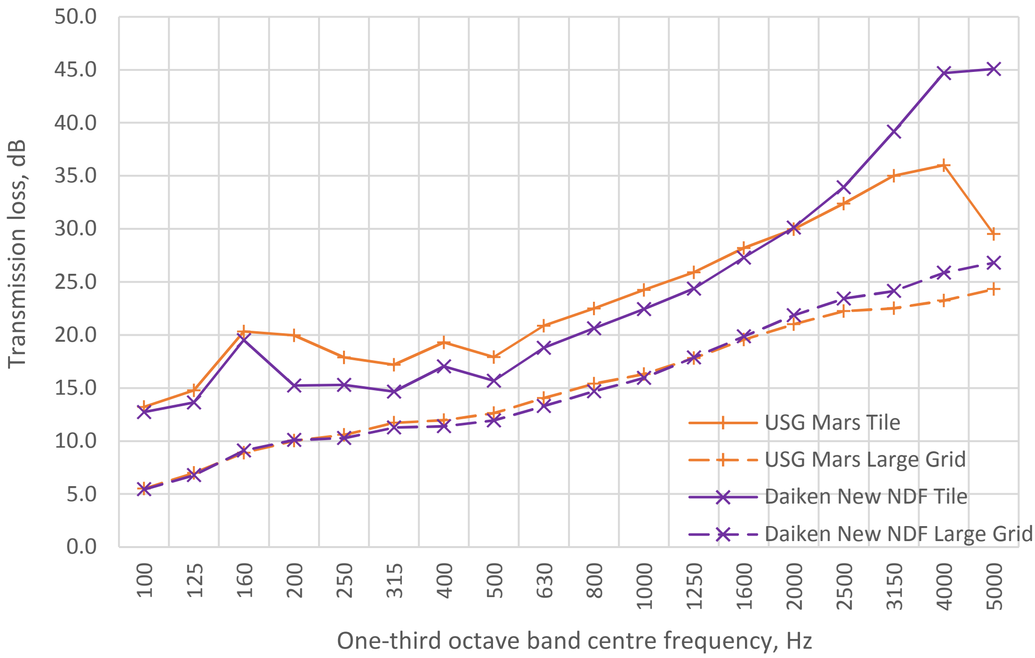
The TL difference for the T&R Interior Systems CMax Combo 35 for the ceiling tile alone to the ceiling tile installed in a suspended ceiling grid showed a large difference above 500 Hz, as plasterboard, is a relatively good product for decreasing sound transmission. However, once the ceiling tiles were installed in the grid, the TL of this product, does not increase to the same extent (although some additional increase over the mineral fibre ceiling tiles is seen).

8.5.2 Leakage of a large suspended ceiling grid

The results in the large suspended grid ceiling showed a similar TL shape to those obtained using the small suspended ceiling grid. Therefore results between the large suspended ceiling grid and single ceiling tile are expected to show similar trends. A comparison of the results for a single ceiling tile and the tiles in a large grid are shown in Graph 8.5a and 8.5b. The results of the TL through the single ceiling tiles are shown as a solid line, and the results of the TL tests in the large suspended ceiling system are shown as a large dashed line.



Graph 8.5a: TL of a single ceiling tile (solid line) and the tile in a large suspended ceiling grid (dashed line) in the large TL facility



Graph 8.5b: TL of a single ceiling tile (solid line) and the tile in a large suspended ceiling grid (dashed line) in the large TL facility

The single ceiling tile results show an increase between 500 Hz and approximately 2,000 Hz (depending on the product). The coincidence 'dip' is seen after this region. The large suspended ceiling system does not exhibit the coincidence dip, with a steady increase over the 100 Hz to

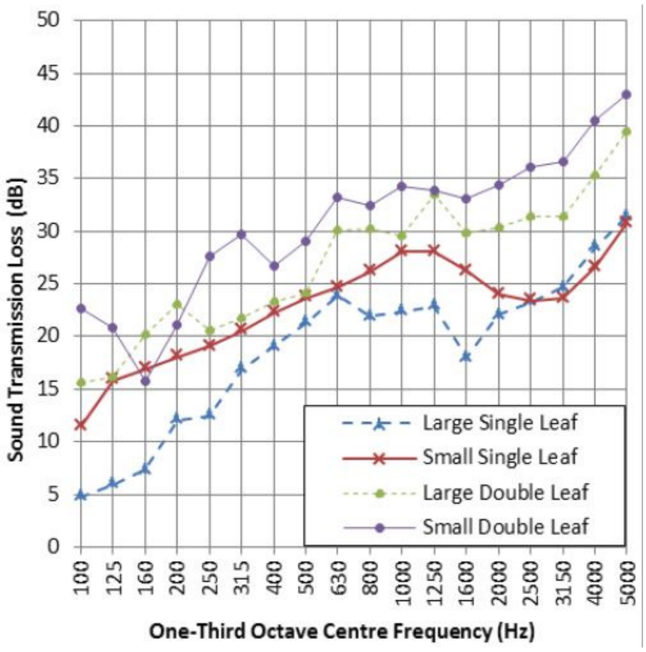
5,000 Hz frequency range. The three thinnest mineral fibre ceiling tiles (Daiken New NDF, USG Mars, and Armstrong Ultima) exhibited a similar difference between the single ceiling tile and large suspended ceiling, with an average difference of 8.5 dB over the 100 Hz to 5,000 Hz frequency range. For all measurements, the TL at each one-third octave band test frequency between the 100 Hz to 5,000 Hz ranged from 0 dB (at the coincidence region of the single tile), to over 18 dB. The AMF Thermatex Silence showed a larger average difference between the two tests of 10 dB, with all results of the single ceiling tile being between 5 dB to 14 dB higher than the large suspended ceiling system. The plasterboard backed T&R CMax Combo 35 composite ceiling tile had the largest average difference of 12 dB between the single ceiling tile and large suspended ceiling system. This product also had the largest differences when considering all frequency bands, with the results between the single ceiling tile and large suspended ceiling grid being between 4 dB and 20 dB.

These results suggest that when ceiling tiles are installed within a suspended ceiling grid, the TL characteristics of the system changes due to the large leakage caused by the suspended ceiling grid. The large differences seen between the individual ceiling tile products when tested through only the ceiling tile are not as pronounced when the ceiling tiles are installed in a suspended ceiling grid.

When considering the comparison between the TL of a single ceiling tile and the TL of a suspended ceiling system, the results suggest that a suspended ceiling grid provides a significant decrease in the TL that the ceiling tile provides.

8.6 Effect of sample size on transmission loss of suspended ceilings

The small TL facility allows a quicker and easier testing facility compared to the large TL facility as well as using less product. If results can correlate well between these two facilities, then the small TL can be used for further product development and research. The TL of single and double wall systems have been previously compared between the two TL facilities at the University of Canterbury[84]. Wareing *et al*[84] tested multiple single and double leaf plywood panels in these two facilities, with the results of the 12 mm plywood single sheet and two 12 mm plywood sheets shown in Graph 8.6. It was concluded that the results from the small TL facility has a similar trend to the results obtained from the tested in the large TL facility (with the coincidence region at a similar frequency, and relatively the same mass controlled region shape curve), but the results from the small TL tests were generally higher than that of the large TL facility. The smaller TL facility changes the edge ratio, wall to area ratio, maximum angle of incidence, as well as the resonant and forced sound paths through the product[54], which accounts for the increase in TL seen in the small facility.

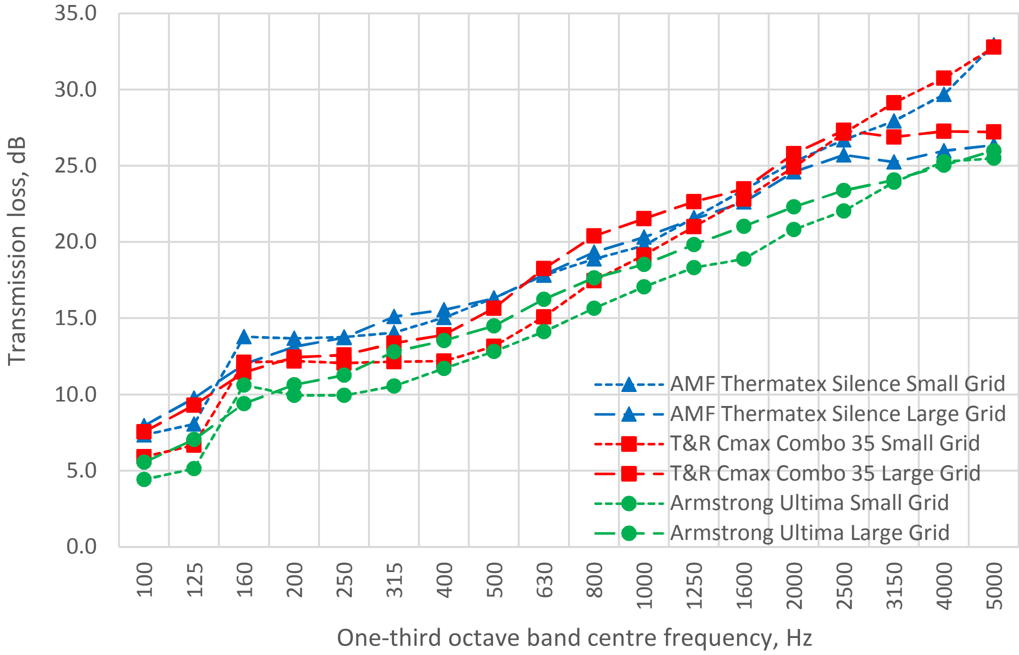


Graph 8.6: TL of a 12 mm single panel and double panel wall system tested in the small and large TL facility at the University of Canterbury[84]

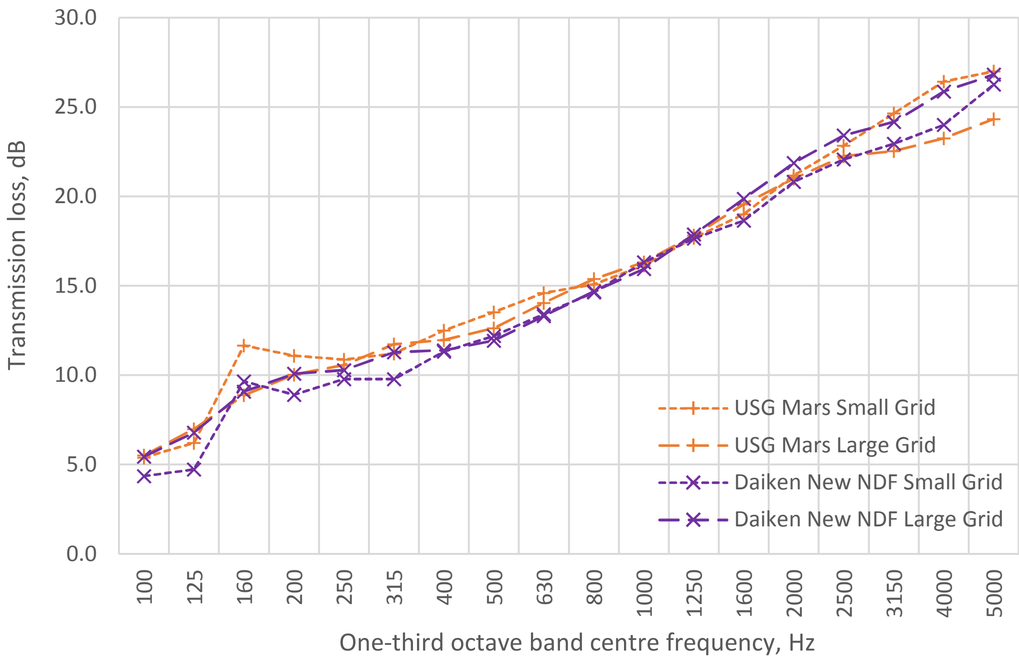
In addition to the parameters above which effect the TL when measured in different sized TL facilities, the area of ceiling tile compared to the grid length changes from the small TL facility (10 m / 1.15m^2) to the large TL facility (26.4 m / 5.76 m^2). The large suspended ceiling system had a larger area of ceiling tile to length of grid than that of the small TL facility and it was expected that results from the large TL facility would consequently have a higher TL. This is opposite to the results that Waring *et al* described, however these are two entirely different systems being compared.

Graph 8.7a and Graph 8.7b show the results of the suspended ceiling grid installed in the small TL facility (small dashed line) to the results of the suspended ceiling in the large TL facility (large dashed lines). It can be seen that the TL of the ceiling tile products installed in the large grid are higher than that in the small grid.

Leakage through the suspended ceiling system at high frequencies is more prominent in the large TL facility, with a slight decrease in TL seen for all products above 2,500 Hz when compared to the small TL facility, except for the Daiken New NDF ceiling tile, which does not exhibit this behaviour.



Graph 8.7a: TL of a small suspended ceiling system (small dashed line) and a large suspended ceiling system (large dashed line) in the small TL facility



Graph 8.7b: TL of a small suspended ceiling system (small dashed line) and a large suspended ceiling system (large dashed line) in the small TL facility

The large TL facility produces, on average, approximately a 0.5 dB higher result over the frequency bands for mineral fibre ceiling tiles, and a 1.2 dB higher result for composite ceiling tiles than that of the small TL facility. The differences between these two facilities can range from 3 dB higher for the large TL facility at the low to medium frequencies (when not considering the increase at 160 Hz for the small TL facility), to a 5 dB higher result for the small TL facility at the high frequencies. However, consistently, the large TL facility results show a 1 dB to 3 dB increase in the one-third octave bands over that measured in the small TL facility.

The TL curves for the tests in the large and small TL facilities show the same trend where the TL increases with frequency at approximately the same rate (1.3 dB increase per one-third octave band increase for the small suspended ceiling system, and a 1.2 dB increase per one-third octave band increase for the large suspended ceiling, on average). The increase in TL is probably due to the increased area of ceiling tile to length of the suspended ceiling grid.

8.7 Summary

The TL provided by a single ceiling tile and a suspended ceiling system has been measured at the University of Canterbury. The TL results show that properties, other than the surface density of the tile affect the TL that a single ceiling tile provides. For example considering the Armstrong Ultima ceiling tile (surface density of 5.2 kg/m^2) and USG Mars ceiling tile (surface density 4.7 kg/m^2), the USG Mars provides a higher sound reduction than the Armstrong Ultima which has a lower surface density for the same thickness.

The leakage of the grid has a major influence on the TL that the ceiling tile provides. The reduction when a ceiling tile is installed in a suspended ceiling grid can range from 0 dB up to 18 dB. The results of the measurements consequently show that the difference in TL when comparing ceiling tiles is much closer when they are installed in a suspended ceiling grid, rather than through the ceiling tile individually.

While there is a small difference between the small and large suspended ceiling system, this was attributed to the area of the suspended ceiling compared to the area of the suspended ceiling grid. In the large TL facility, there was more area of ceiling tile to length of grid, and therefore a higher TL was observed.

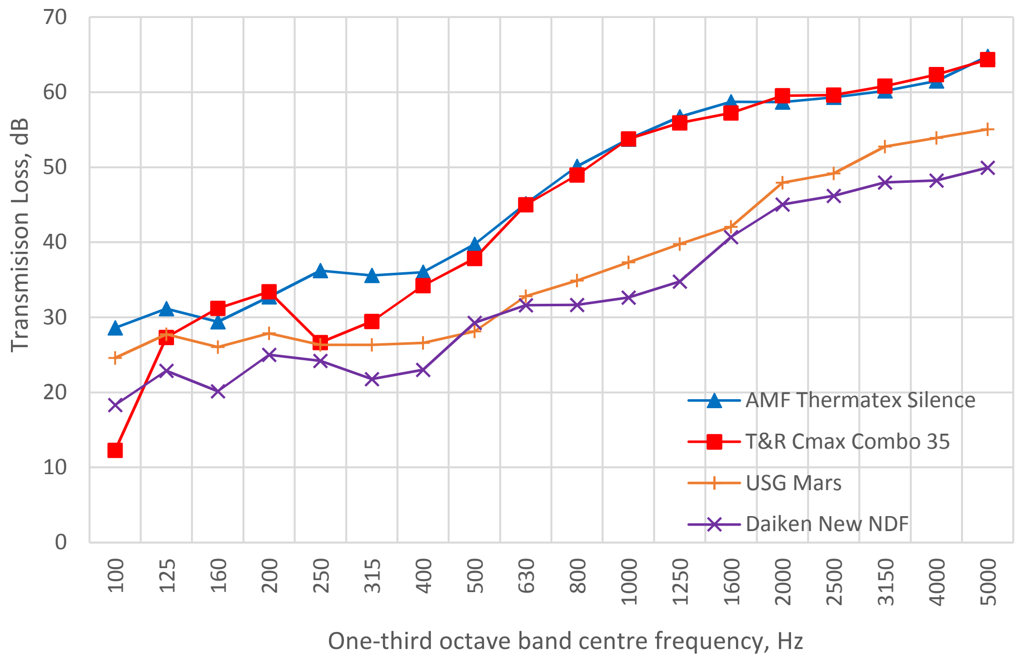
9.0 CFN Facility Results

9.1 Overview

This chapter presents ceiling tile product test results obtained in the commissioned CFN facility. Four different ceiling tile products; three mineral fibre ceiling tiles, and one composite ceiling tile were placed in turn in the CFN facility and their TL determined. Four different thicknesses of absorption were added to the plenum, over the ceiling tiles in turn for each ceiling tile. The absorption was in the form of fibrous ceiling tiles that were laid on top of each ceiling tile product in turn. The thickness of the absorption was 15 mm, 25 mm, 40 mm, and 100 mm. This absorption was cut (where needed) to fit snug on top of the ceiling tiles within the suspended ceiling grid.

9.2 Ceiling tile products

The tabulated TL and single number CAC / $D_{n,c,w}$ ratings are given in Appendix A.X, with the summary of the test results shown in Graph 9.1. The results show, as expected, that as the surface mass of the ceiling tile increases, the TL of the suspended ceiling system increases. The Daiken ceiling tile has the lowest surface mass of 3.3 kg/m^2, and is shown to have the lowest TL, with the AMF Thermatex Silence ceiling tile being the heaviest at 10.8 kg/m^2, and is shown to have the highest TL.



Graph 9.1: Transmission loss of four different ceiling tile products in the CFN facility developed at the University of Canterbury

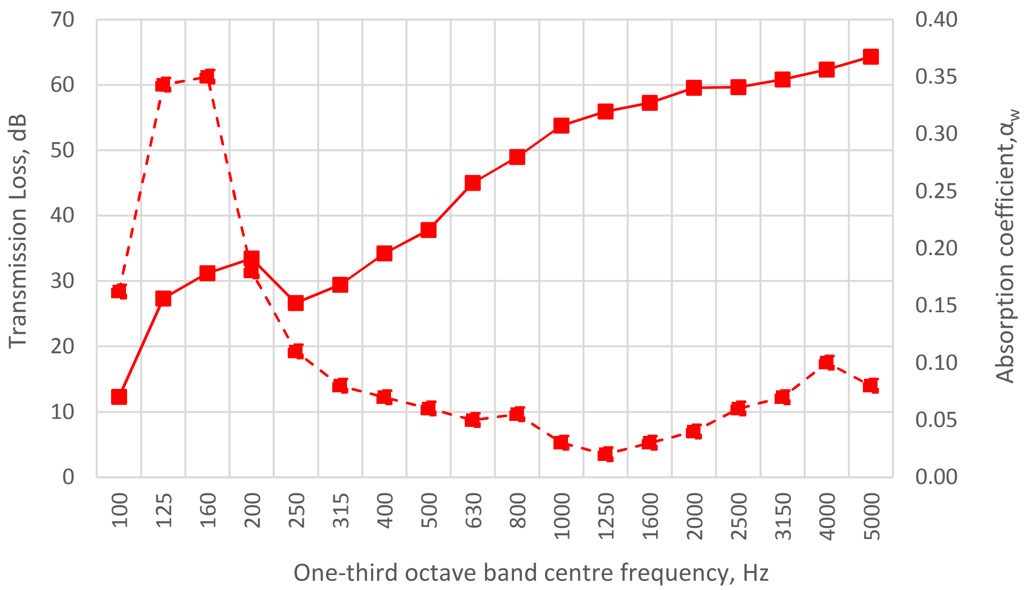
There are three regions which may be seen in the plenum sound path TL curves for the four ceiling tile products. The first region (below 200 Hz) is typically flat. Between approximately 200 Hz and 500 Hz, the TL curve is still approximately flat, however the TL in this region increases with increasing mass added to the system. There is a greater difference between the measured Tl between 200 Hz and 500 Hz than below 200 Hz for when comparing each product. The third region, above 500 Hz is probably a mass controlled region where the Tl increases with the mass of the ceiling tile.

Through the expected mass controlled region, above 500 Hz, the TL increases by approximately 12 dB per one-third octave band as the surface density doubles. The USG mars ceiling tile has a 4.7 kg/m^2 surface density and the T&R Interior Systems CMax Combo 35 ceiling tile has a surface density of 10.2 kg/m^2 and the average difference between these two products above 500 Hz is approximately 12 dB.

The decrease seen at 250 Hz for the T&R Interior System CMax Combo 35 is probably due to the reflective surface on the roof and the back of the ceiling. The back face of this ceiling tile is plasterboard, so it reflects sound more readily, as seen in Graph 4.2. This is put down to a mode between the plasterboard backing of the ceiling tile and the roof of the CFN facility, as the mineral fibre ceiling tile products that afford some absorption to the back do not show this trend.

The trend of the mineral fibre ceiling tiles is similar across all products tested. The difference seen between the AMF Thermatex Silence, USG Mars, and Daiken New NDF ceiling tile products was attributed to the surface density, as the Daiken New NDF had the lowest surface mass of 3.3 kg/m^2 the USG Mars had a slightly higher surface density of 4.7 kg/m^2, with the AMF Thermatex Silence having a much higher surface density of 10.8 kg/m^2.

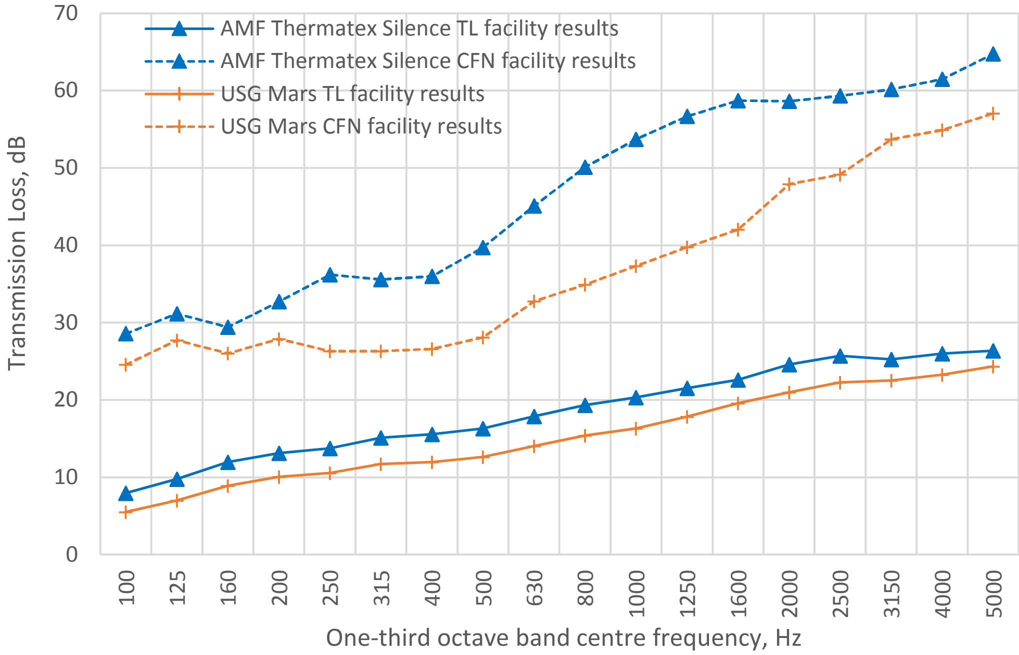
The composite ceiling tile showed dip in the low frequency region (below 200 Hz) at 100 Hz. A second dip occurred in the mid frequency region (200 Hz to 500 Hz), at the 250 Hz one third octave band. The TL dip at 250 Hz is expected to be due to the reflective nature of the plasterboard backing and the likelihood of a standing wave between the plasterboard and roof. This is not generally evident for the mineral fibre tiles which offer some absorption on the face of the tile in the plenum. The back face absorption of the ceiling tile compared to the plenum sound path TL for the T&R Interior Systems CMax Combo 35 is shown in Graph 9.2.



Graph 9.2: Transmission loss (solid line) compared to the back face absorption (dashed line) for the T&R Interior Systems CMax Combo 35

9.3 Comparison with transmission loss measurements

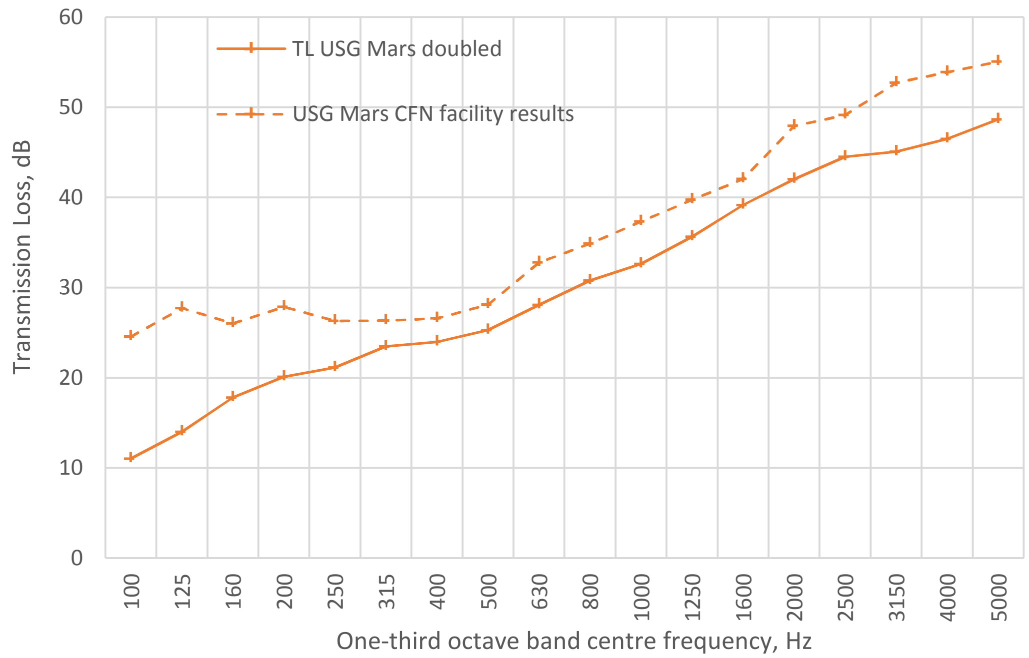
When comparing the TL results of a suspended ceiling system in the TL facility described in Chapter 8 to the same ceiling tile measured in the CFN facility, it can be seen that there is a large difference in TL. Graph 9.3 shows the AMF Thermatex silence and USG Mars mineral fibre ceiling tiles measured in the TL facility (solid line) compared to that tested in the CFN facility (dashed line).



Graph 9.3: Comparison between results from the TL facility and CFN facility at the University of Canterbury for two ceiling tile products

For the AMF Thermatex Silence ceiling tiles, the TL on average is approximately 28 dB higher (between 17 dB to 38 dB) in the CFN facility than that measured in the TL facility. For the USG Mars ceiling tiles, the TL on average was 21 dB higher (between 15 dB to 31 dB) when measured in the CFN facility.

The TL through the plenum sound path is over twice that of that measured in the large TL facility. This is shown in Graph 9.4, where the USG Mars results from the large TL facility (solid line) are doubled and compared with the results measured in the CFN facility (dashed line). The difference between the two tests probably due to the sound dissipated as it propagates through the plenum.

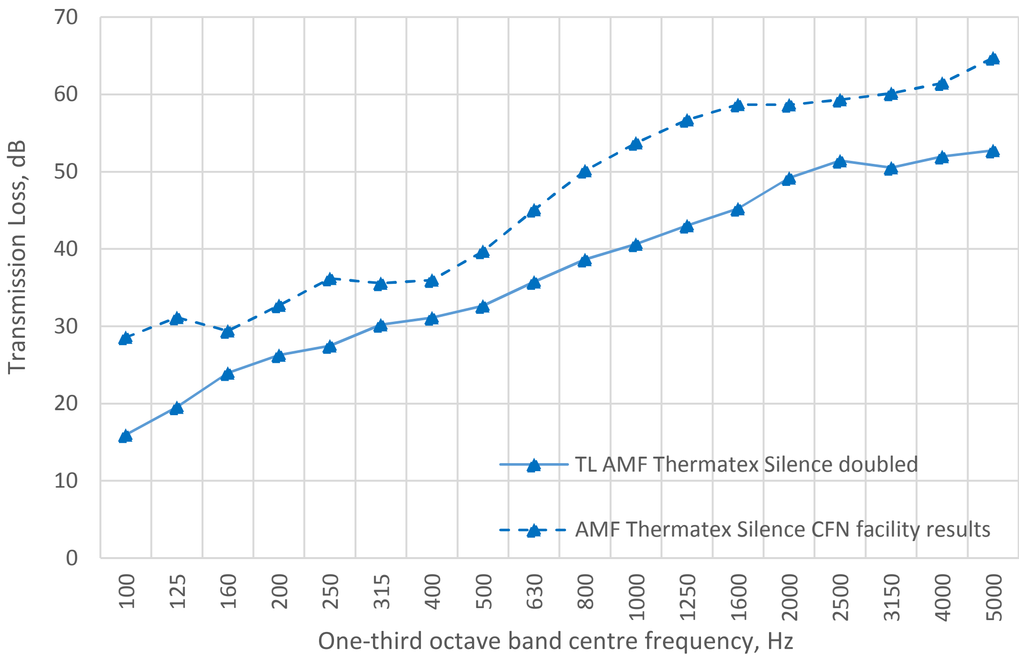


Graph 9.4: Difference between the doubled TL results in the large TL facility (solid line) and the results through the plenum sound path in the CFN facility (dashed line) for the USG Mars ceiling tiles

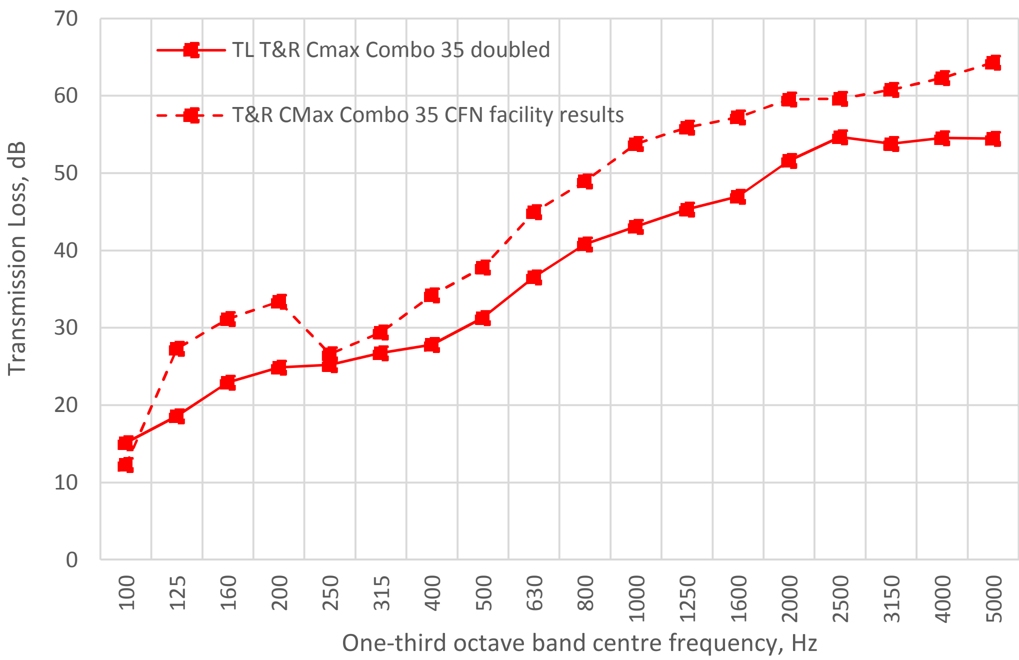
Graphs 9.5 shows the TL doubled for the AMF Thermatex Silence and compared to the plenum sound path TL measured in the CFN facility. Graph 9.6 shows this for the T&R CMax Combo 35, and Graph 9.7 shows this for the Daiken New NDF ceiling tiles.

For all comparisons, there is a difference between that measured in the CFN facility and the doubled results from the large TL facility. This is most prominent in the higher surface density ceiling tiles (AMF Thermatex Silence and T&R CMax Combo 35), except at 100 Hz and 250 Hz for the T&R CMax Combo 35. The results from the CFN facility were approximately 5 dB higher, ranging from approximately 5 dB to 14 dB for the AMF Thermatex Silence ceiling tiles and 5 dB and 11 dB for the T&R CMax Combo 35 ceiling tile.

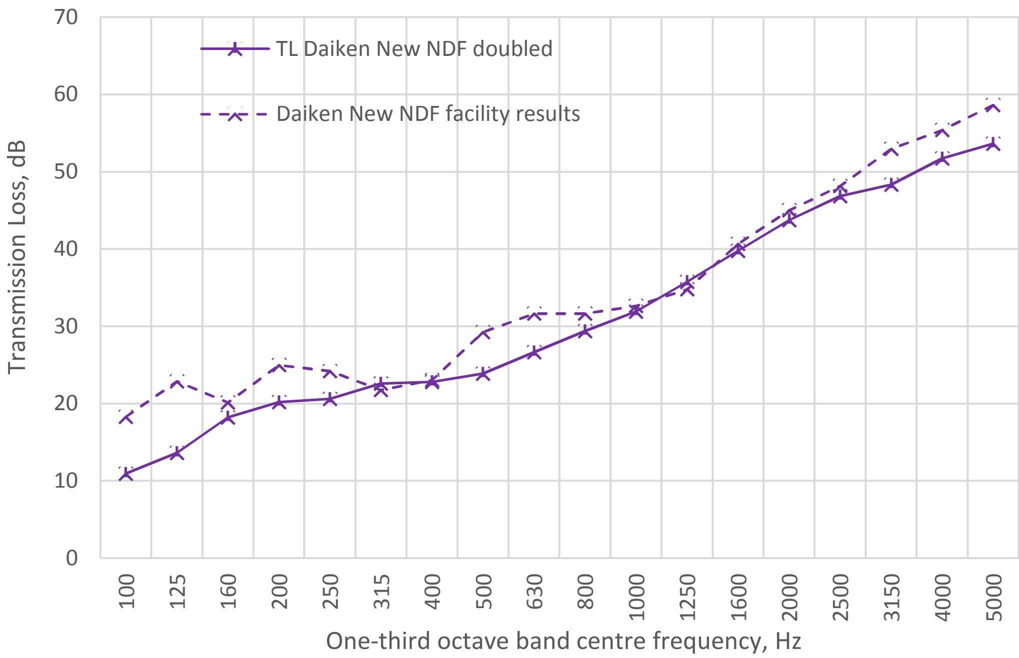
The difference between the results doubled from the large TL measurements and the results in the CFN facility are is much smaller for the Daiken New NDF ceiling tile than the three other ceiling tiles tested. The difference ranged from 0 dB to 10 dB.



Graph 9.5: Difference between the doubled TL results in the large TL facility (solid line) and the results through the plenum sound path in the CFN facility (dashed line) for the AMF Thermatex Silence ceiling tiles



Graph 9.6: Difference between the doubled TL results in the large TL facility (solid line) and the results through the plenum sound path in the CFN facility (dashed line) for the T&R CMax Combo 35 ceiling tiles



Graph 9.7: Difference between the doubled TL results in the large TL facility (solid line) and the results through the plenum sound path in the CFN facility (dashed line) for the Daiken New NDF ceiling tiles

The results from the Daiken New NDF ceiling tile were surprising as this ceiling tile had the highest absorption on the rear face when compared to all other ceiling tiles so was expected to have the largest difference. This result may be explained due to the thickness of the Daiken New NDF ceiling tile. The Daiken New NDF ceiling tile was 12 mm thick (compared to 19 mm thick for the USG Mars, 35 mm thick for the T&R CMax Combo 35 ceiling tile, and 42 mm thick for the AMF Thermatex Silence ceiling tile). This may create less of a seal between the ceiling tile and the vertical member of the 'T' suspended grid system. Above 1,000 Hz, the difference between the TL measured in the CFN facility and doubled from the large grid TL results are very comparable.

9.4 Plenum absorption

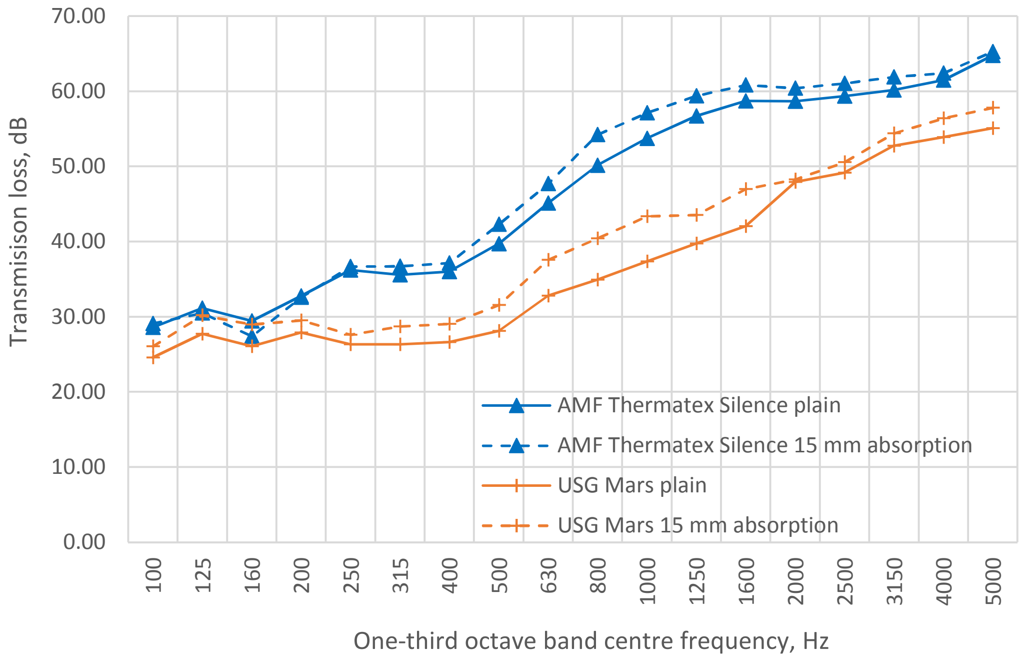
Four different thicknesses of absorption were added separately to the rear of the ceiling tiles to the plenum to determine the effect that absorption in the plenum has on the TL through the plenum sound path. 15 mm, 25 mm, 40 mm and 100 mm fibrous ceiling tiles were installed on top of each ceiling tile product tested. The mass of the acoustic absorption added in turn over the ceiling tiles the probable cause of the additional TL seen in the results, with the sound absorption provided by the additional absorption product giving some minor increase.

The full tabulated results are shown in Appendix A.X.

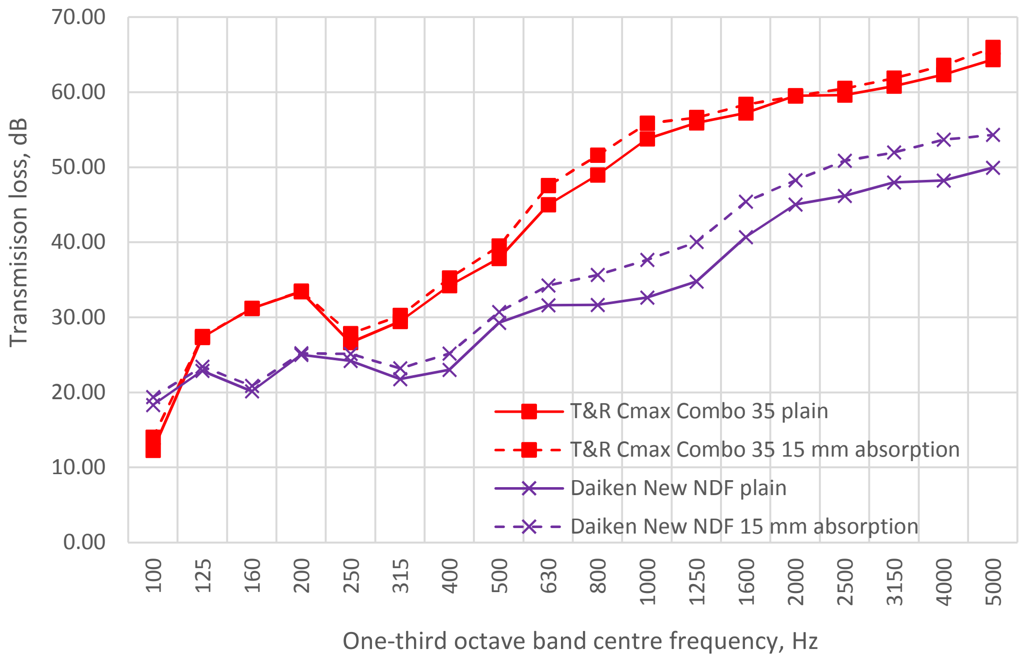
10.3.1 15 mm fibrous absorption in the plenum

In the first region (below 200 Hz) there is little difference when 15 mm of absorption is added to the plenum. In the second region (between 200 Hz and 500 Hz) there is a slight increase in the ceiling tile products that have a lower surface density, with the higher surface density products showing very little increase in this region. Through the third region (above 500 Hz), the TL increases. As this is probably the mass controlled region, the TL increases due to the increased mass of the absorption in the plenum on the back of the ceiling tiles.

The increase above 500 Hz for the AMF Thermatex Silence was on average 2 dB (ranging between 1 dB and 4 dB), with the T&R Interior System CMax Combo 35 average increase of 1.5 dB (ranging between 0 dB and 3 dB). The USG Mars showed an average increase above 500 Hz of 3 dB (ranging between 1 dB and 6 dB), and the Daiken New NDF showed an average increase of 4 dB (ranging between 2 and 6 dB). The average increase shows a similar trend that when the mass increases, the TL increases by 6 dB.



Graph 9.8a: TL through the plenum sound path without absorption (plain, solid line), and with 15 mm absorption added to the plenum (15 mm absorption, dashed line)

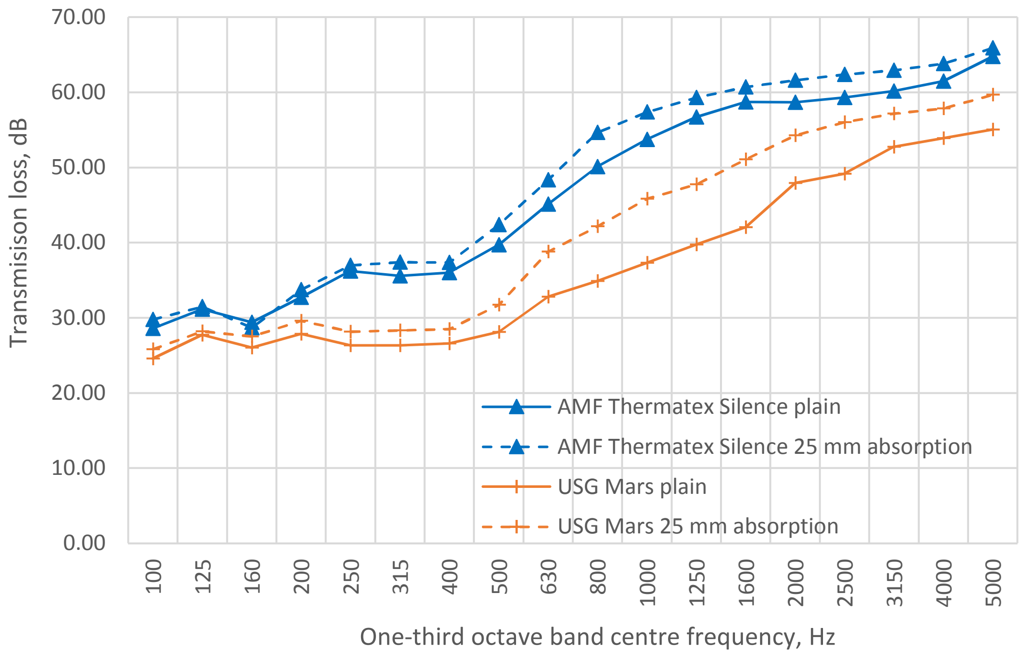


Graph 9.8b: TL through the plenum sound path without absorption (plain, solid line), and with 15 mm absorption added to the plenum (15 mm absorption, dashed line)

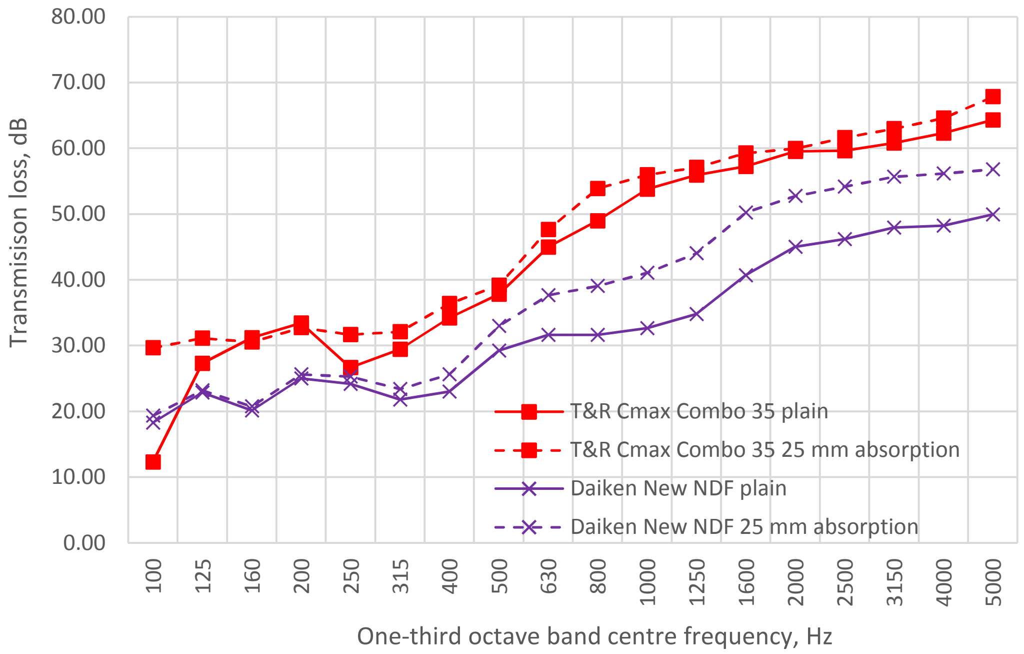
The change in TL with the 15 mm fibrous absorption is more apparent in the thinner ceiling tiles tested. It is surprising to see negligible change to the TL of the T&R CMax Combo 35 ceiling tile with the 15 mm absorption added to the rear face. It was expected that this ceiling tile would show the largest increase due to the reflective back face. The decrease seen at 250 Hz is reduced slightly, but still is very apparent compared to the mineral fibre ceiling tiles tested.

9.3.2 25 mm fibrous absorption in the plenum

25 mm fibrous insulation was laid over all ceiling tile products in the CFN facility, and the TL through the plenum sound path was tested. The results from the tests are shown in Graph 9.9a and 9.9b, that compare the no absorption tests (solid line) to that with 25 mm of fibrous absorption in the plenum (dashed line).



Graph 9.9a: TL through the plenum sound path without absorption (plain, solid line), and with 25 mm absorption added to the plenum (25 mm absorption, dashed line)



Graph 9.9b: TL through the plenum sound path without absorption (plain, solid line), and with 25 mm absorption added to the plenum (25 mm absorption, dashed line)

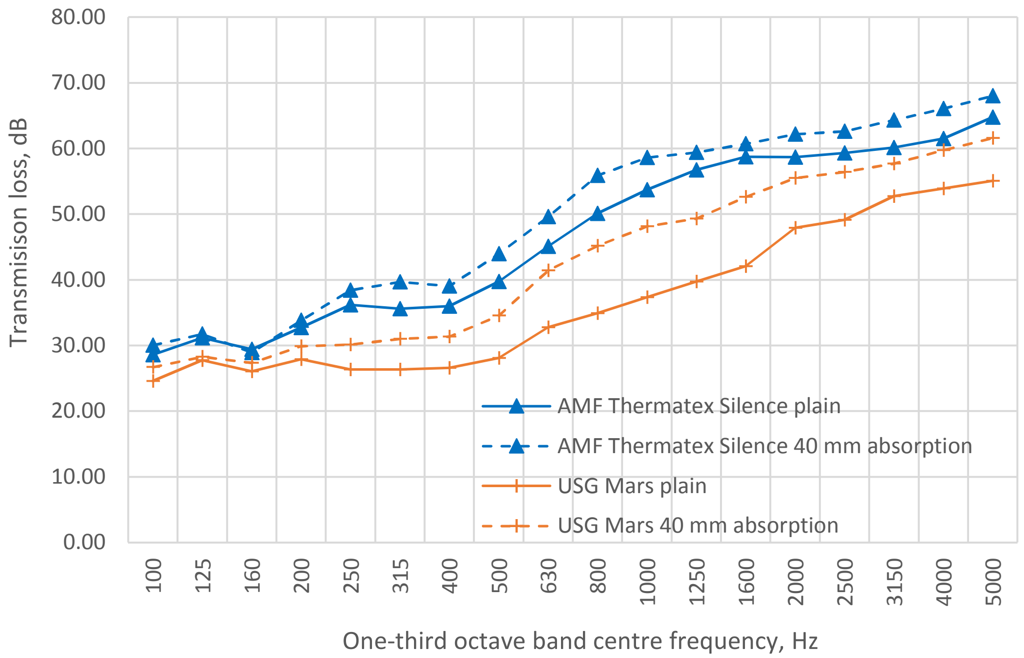
In the first region (below 200 Hz) there is still little difference when 25 mm of absorption is added to the plenum. In the second region (between 200 Hz and 500 Hz) there is a slight increase in the TL between no absorption in the plenum and 25 mm of absorption in the plenum. The addition of absorption has a greater effect on ceiling tile products that have a lower surface density, with the higher surface density products showing very little increase in this region. Through the third region (above 500 Hz), the TL increases. As this is probably the mass controlled region, the TL increases likely due to the increased mass of the absorption in the plenum on the back of the ceiling tiles.

The increase above 500 Hz for the AMF Thermatex Silence was on average 3 dB (ranging between 1 dB and 4 dB), with the T&R Interior System CMax Combo 35 average increase of 2 dB (ranging between 1 dB and 5 dB). The USG Mars showed an average increase above 500 Hz of 6 dB (ranging between 4 dB and 9 dB), and the Daiken New NDF showed an average increase of 7.5 dB (ranging between 4 and 10 dB). The increase over the third region is a bit more than that predicted by the mass law equation of doubling the surface density to increase the TL by 6 dB, as the surface density of the Daiken New NDF is 3.3 kg/m^2, and the surface density of the absorption was approximately 2.5 kg/m^2, however there is an average increase above 500 Hz of 7.5 dB, so some sound is dissipated with the addition of the absorption in the plenum. This is also seen in the results of the USG Mars ceiling tile, with a surface density of 4.7 kg/m^2, the increase in TL with the absorption added over should be less than 3 dB, however an average of a 6 dB increase is seen above 500 Hz.

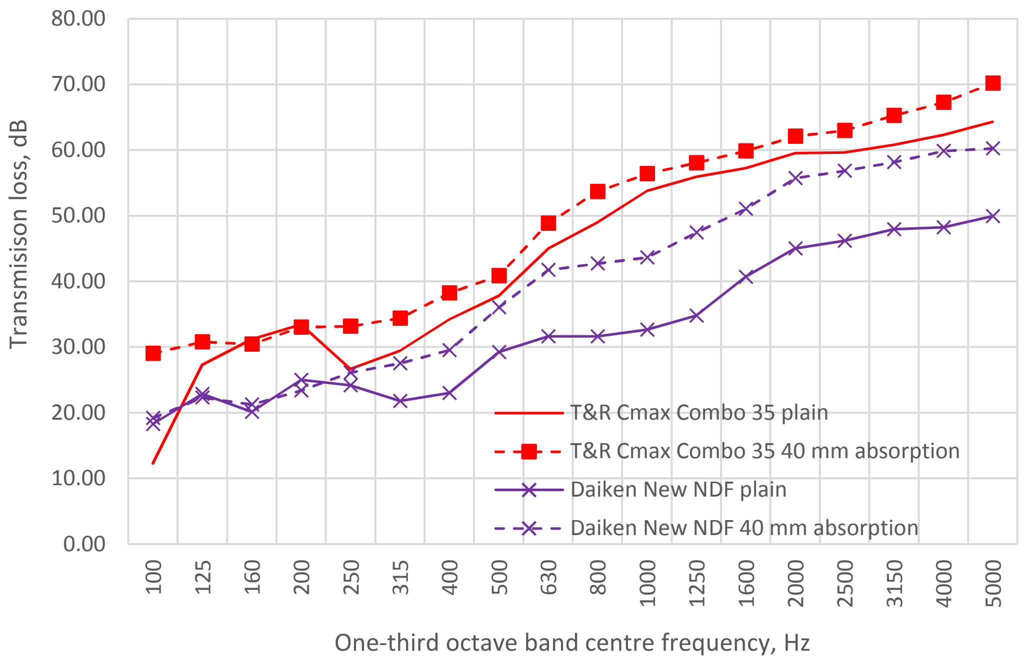
As with the addition of 15 mm fibrous insulation, the Daiken New NDF ceiling tile results show that the TL increase is larger than any other ceiling tile tested. The decrease seen at 250 Hz in the T&R CMax Combo 35 ceiling tile disappears when 25 mm of acoustic absorption is added above this. This level of absorption is expected to absorb the sound being reflected between the rear plasterboard surface of the ceiling tile and roof, so the mode between these surfaces is minimised.

9.3.3 40 mm fibrous absorption in the cavity

40 mm fibrous absorption was added to the plenum of the CFN facility, above all ceiling tile products tested in this research. The results for these tests are shown in Graph 9.10a and 9.10b, and compared to the testing with no absorption in the plenum (solid line).



Graph 9.10a: TL through the plenum sound path without absorption (plain, solid line), and with 40 mm absorption added to the plenum (40 mm absorption, dashed line)



Graph 9.10b: TL through the plenum sound path without absorption (plain, solid line), and with 40 mm absorption added to the plenum (40 mm absorption, dashed line)

In the first region (below 200 Hz) there is still little difference when 40 mm of absorption is added to the plenum. In the second region (between 200 Hz and 500 Hz) there is marked increase in the TL between no absorption in the plenum and 25 mm of absorption in the plenum. The addition of absorption has a greater effect on ceiling tile products that have a lower surface density, however an increase of the higher surface density products shows an increase through this region also. Through the third region (above 500 Hz), the TL increases. As this is probably the mass controlled region, the TL increases likely due to the increased mass of the absorption in the plenum on the back of the ceiling tiles.

The increase between the 200 Hz and 500 Hz region from when there was no absorption in the plenum for the AMF Thermatex Silence ceiling tiles was on average 3 dB (ranging between 1 dB and 4 dB), with an average increase between 200 Hz and 500 Hz of 4 dB seen for the T&R CMax Combo 35 ceiling tile (ranging from 0 to 6 dB). The average increase was 4 dB for the USG Mars ceiling tile (ranging from 2 dB to 6 dB), with an increase of 4 dB seen in the Daiken New NDF between 200 Hz and 500 Hz (ranging from 0 to 7 dB).

The increase above 500 Hz for the AMF Thermatex Silence was on average 3 dB (ranging between 2 dB and 5 dB), with the T&R Interior System CMax Combo 35 average increase of 4 dB (ranging between 2 dB and 6 dB). The USG Mars showed an average increase above 500 Hz of 8 dB (ranging between 6 dB and 11 dB), and the Daiken New NDF showed an average increase of 11 dB (ranging between 10 and 12 dB). Again, the increase over the third region is more than that predicted by the mass law equation of doubling the surface density to increase the TL by 6 dB, as the surface density of the USG Mars is 4.7 kg/m^2, and the surface density of the absorption was approximately 4 kg/m^2, however there is an average increase above 500 Hz of 8 dB, so some sound is dissipated with the addition of the absorption in the plenum. Between 200 Hz and 500 Hz, the increase is over half that expected according to mass law of 4 dB.

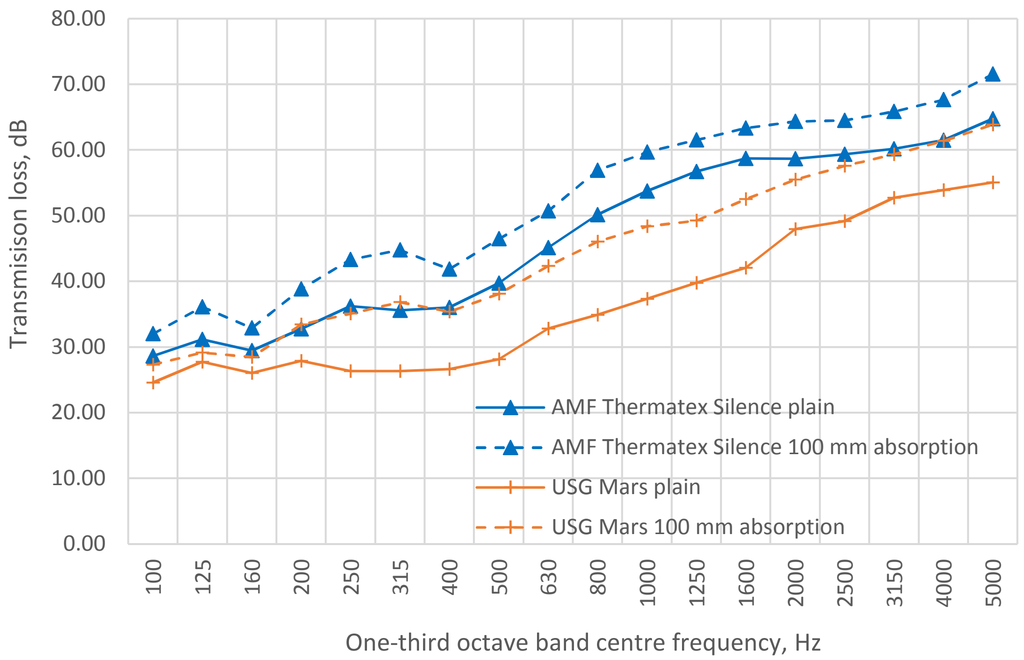
The increase in TL for the T&R CMax Combo 35 composite ceiling tile at the low frequencies is increased so that it follows a similar trend to the mineral fibre ceiling tiles tested in this research. The low frequency dips at 100 Hz and 250 Hz are removed, and the TL curve is essentially flat between 100 Hz and 500 Hz.

The transmission loss afforded by the USG Mars and the Daiken New NDF with 40 mm of absorption behind are getting in the order to that afforded by the a high mass ceiling tile. This is expected because the surface density of the ceiling tile and absorption combination are in the order of 8 kg/m^2 to 9 kg/m^2, which is just below the surface density of the T&R CMax Combo 35 ceiling tile (10.2 kg/m^2).

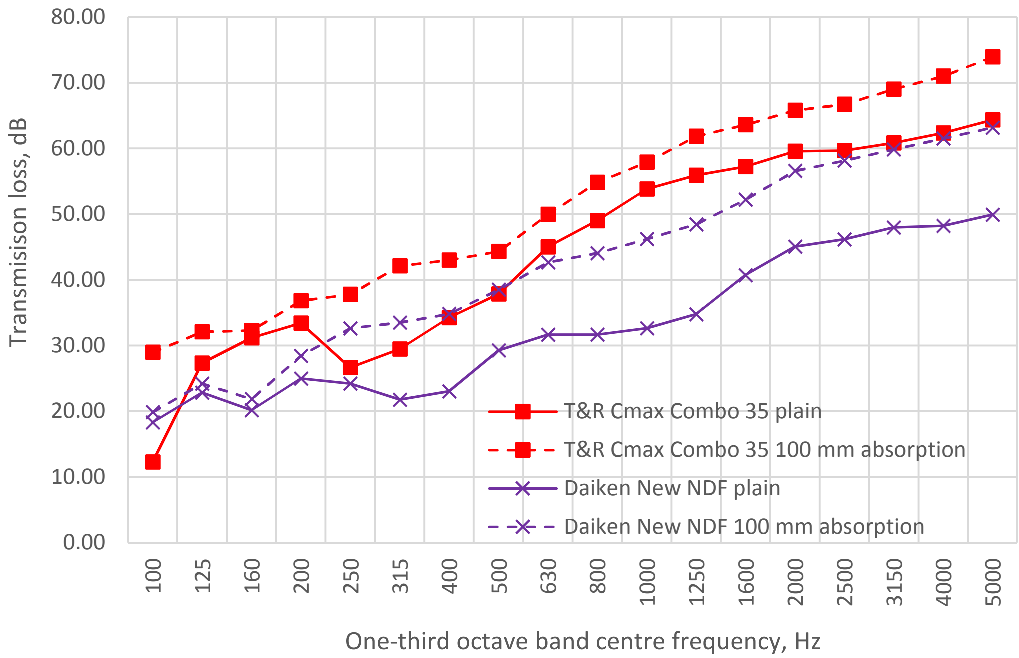
While there was an increase in the TL of the AMF Thermatex Silence and T&R CMax Combo 35 ceiling tile, the increase was small compared to the two other ceiling tiles tested in this research. This is expected to be due to the already high TL of the ceiling tile, as the mass of the absorption is less than half that of the ceiling tile.

9.3.4 100 mm fibrous absorption in the plenum

The addition of 100 mm of fibrous insulation to the plenum showed the largest increase in TL over any other combination, which was expected due to the large amount of absorption and surface density that 100 mm absorption provides. Graph 9.11a and 9.11b show the TL when 100 mm of fibrous absorption is added to the plenum (dashed line) compared to the TL without absorption to the cavity (solid line).



Graph 9.11a: TL through the plenum sound path without absorption (plain, solid line), and with 100 mm absorption added to the plenum (100 mm absorption, dashed line)



Graph 9.11b: TL through the plenum sound path without absorption (plain, solid line), and with 100 mm absorption added to the plenum (100 mm absorption, dashed line)

In the first region (below 200 Hz) there is an increase in the transmission loss at low frequencies (between 1 and 4 dB for each ceiling tile) when 100 mm of absorption is added to the plenum. In the second region (between 200 Hz and 500 Hz) there is relatively large increase in the TL between no absorption in the plenum and 25 mm of absorption in the plenum. The addition of absorption has a greater effect on ceiling tile products that have a lower surface density, however an increase of the higher surface density products shows an increase through this region also. Through the third region (above 500 Hz), the TL increases. As this is probably the mass controlled region, the TL increases likely due to the relatively large increase in mass due to the absorption in the plenum on the back of the ceiling tiles.

The increase at low frequencies had a large effect on the ceiling tiles that had a higher surface density, with an average difference of 3 dB below 200 Hz for the AMF Thermatex Silence, and 7 dB for the T&R Interior Systems CMax Combo 35. The large increase seen in the T&R Interior Systems is due to the large increase at 100 Hz. With this removed the average TL below 200 Hz Is 3 dB. The lower mass ceiling tiles exhibited a lower increase in TL below 200 Hz, with an average increase of 2 dB for the USG Mars and 1.5 dB for the Daiken New NDF ceiling tile. This shows that as the mass decreases, the change in TL decreases.

The increase between the 200 Hz and 500 Hz region from when there was no absorption in the plenum for the AMF Thermatex Silence ceiling tiles was on average 7 dB (ranging between 6 dB and 9 dB), with an average increase between 200 Hz and 500 Hz of 8.5 dB seen for the T&R CMax Combo 35 ceiling tile (ranging from 3 to 13 dB). The average increase was 9 dB for the USG Mars ceiling tile (ranging from 5 dB to 11 dB), with an increase of 9 dB seen in the Daiken New NDF between 200 Hz and 500 Hz (ranging from 4 to 12 dB).

The increase above 500 Hz for the AMF Thermatex Silence was on average 6 dB (ranging between 4 dB and 7 dB), with the T&R Interior System CMax Combo 35 average increase of 7 dB (ranging between 4 dB and 10 dB). The USG Mars showed an average increase above 500 Hz of 9 dB (ranging between 7 dB and 11 dB), and the Daiken New NDF showed an average increase of 12 dB (ranging between 11 and 13 dB). The increase over the third region is more than that predicted by the mass law equation of doubling the surface density to increase the TL by 6 dB for the lower surface density ceiling tiles. The higher surface density ceiling tiles showed a trend very similar to the mass law. The surface density of the absorption was 10 kg/m^2, so for the T&R Interior Systems CMax Combo 35, the mass was effectively doubled, and an average of a 7 dB increase was seen over the expected mass law range.

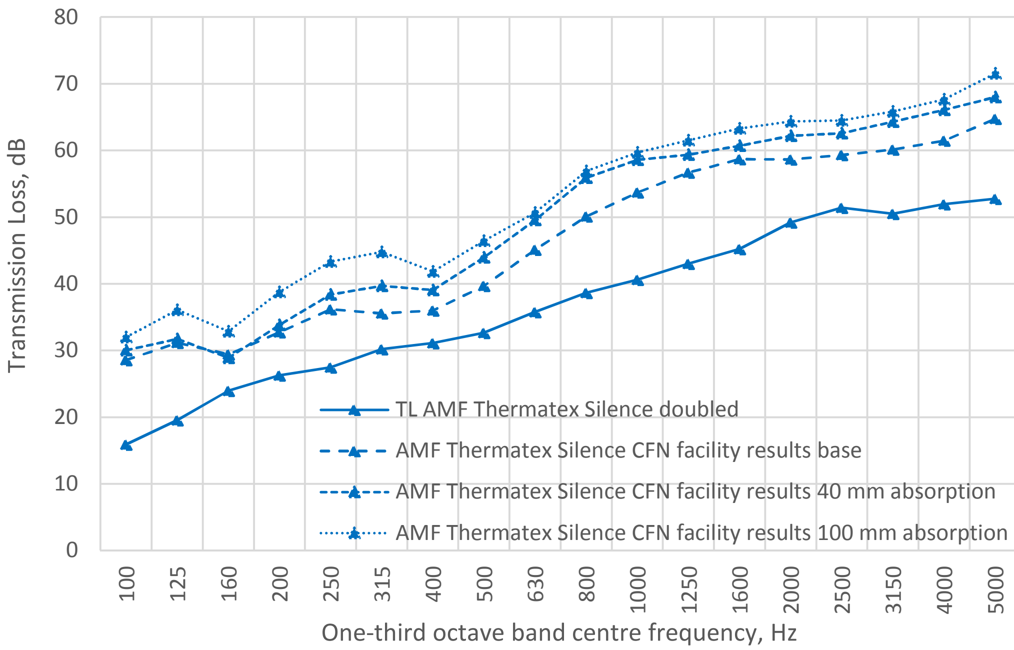
The transmission loss afforded by the USG Mars and the Daiken New NDF with 100 mm of absorption behind is similar (in some cases higher) than that of a high surface density ceiling tile without absorption in the plenum. This is expected because the surface density of the ceiling tile and absorption combination are in the order of 13 kg/m^2 to 15 kg/m^2, which is higher than the high surface density ceiling tiles (10.8 kg/m^2 for the AMF Thermatex Silence, and 10.2 kg/m^2 for the T&R Interior Systems CMax Combo 35 ceiling tile).

9.5 Discussion

The TL of the plenum sound path can be split into three regions. The first region (below 200 Hz) is typically flat, providing a relatively low TL. Between approximately 200 Hz and 500 Hz, the TL curve is still approximately flat, however the TL is higher than that below 200 Hz and is affected more by the mass of the ceiling tile. The third region, above 500 Hz is probably a mass controlled region where the TL increases with the mass of the ceiling tile.

Through the expected mass controlled region, above 500 Hz, the TL increases by approximately 12 dB per one-third octave band as the surface density doubles. The USG mars ceiling tile has a 4.7 kg/m^2 surface density and the T&R Interior Systems CMax Combo 35 ceiling tile has a surface density of 10.2 kg/m^2 and the average difference between these two products above 500 Hz is approximately 12 dB.

The sound transmission between the two rooms, through the plenum can be described as the plenum sound path where sound travels through the suspended ceiling system into the plenum, through the plenum, then back through the suspended ceiling system into an adjacent room. The TL of a suspended ceiling doubled does not give the same results when the same ceiling tile is tested in the CFN facility. This is probably due to sound being dissipated as it travels through the plenum. The TL through the plenum sound path is further increased when additional absorption is added to the plenum, on top of the ceiling tiles. Graph 9.12 shows the TL results from the large TL facility doubled (solid line) compared to the base CFN facility results (large dashed line), with 40 mm fibrous absorption is added to the cavity (small dashed line), and when 100 mm of fibrous absorption is added to the plenum (dotted line) for the AMF Thermatex Silence ceiling tile.



Graph 9.12: TL results doubled (solid line) compared to the plenum sound path TL results with none (large dashed line), 40 mm (small dashed line), and 100 mm (dotted line), absorption added to the plenum

The TL through the plenum sound path is between 5 dB and 14 dB higher than the TL measured in the large suspended ceiling grid doubled. With 40 mm of fibrous absorption added to the cavity, this increases to between 5 dB and 18 dB difference, and with 100 mm of fibrous absorption in the plenum, this increases to 9 dB and 19 dB difference in results. This shows that absorption in the plenum plays a significant role in the reduction of sound between spaces when the predominant sound path is through the plenum.

When thick absorption is added to the plenum (> 90 mm), the TL at these low frequencies also increase, which is not seen when thinner absorption is added to the plenum. This is expected due to the thicker the absorption, the better the absorption product is at absorbing sound at low frequencies. Within thin absorption product, the low frequencies do not get absorbed readily, and are therefore are more readily transmitted through the plenum sound path. Within thick absorption, the low frequencies are absorbed more readily, and therefore are absorbed rather than transmitted through the plenum.

It has been seen that products that have a reflective backing (T&R CMax Combo 35 composite ceiling tile), there is a dip in the TL curve when tested in the CFN facility, which is expected to be due to the mode of the ceiling plenum. The roof of the plenum, and rear of the ceiling tile are both highly reflective, (both have absorption coefficients generally under 0.1 (between 0.1 and 0.3 for the T&R CMax Combo 35 ceiling tile between 100 Hz and 250 Hz), so therefore sound reflect in this plane easily compared to the mineral fibre ceiling tiles that have a higher rear surface absorption coefficient. With the addition of 25 mm of fibrous insulation or thicker installed on the rear surface of a reflective backing ceiling tile, this decrease in TL is reduced to negligible levels.

9.6 Summary

There are typically three regions associated with the plenum sound path. These three regions are a low frequency region (below 200 Hz), where the TL does not increase as the frequency increases; a mid-frequency region (200 Hz to 500 Hz), where the TL does not increase, but gives a higher TL than in the low frequency region; and a high frequency region (above 500 Hz), where the TL increases with frequency at a higher rate.

It has been shown that the TL through the plenum sound path is greater than that through a suspended ceiling system twice (double the TL results measure din the Tl facility). This shows that sound is dissipated when it travels through the plenum space.

This research shows that when absorption is added to the plenum, the TL increases. With a larger thickness of absorption is added to the plenum, above the ceiling tiles, a lower surface density ceiling tile can perform as well as a higher mass ceiling tile without absorption behind. The addition of fibrous absorption to the cavity can increase the TL through this path considerably without having to install complex baffle blocks, hanging mass loaded barrier, or other in ceiling treatment.

The increase in TL when acoustic absorption is added over top of the ceiling tiles is expected to be mostly due to the additional mass afforded by the acoustic absorption product. However, there is an increase over that predicted by mass law (6 dB per doubling of surface density). This effect is expected to be put down to the additional absorption added to the plenum on top of the ceiling tiles, as it absorbs some sound as the sound propagates through the plenum.

10.0 Conclusions and Further Research

10.1 Conclusions

This research was concerned with the TL through the plenum sound path, and exploration of the effect of absorption added to the plenum space, on top of the ceiling tiles. This was investigated by firstly determining the absorption in the plenum.

The absorption offered by the back face of the ceiling tile was determined using the decay method outlined in ISO 354:2003, and the reverberation room at the University of Canterbury. The results from these measurements showed that the absorption afforded by the back face of the ceiling tile was lower than that on the front face. The sound absorption of four thicknesses of acoustic absorption (15 mm, 25 mm, 40 mm, and 100 mm) that were added in turn over the ceiling tiles were also measured using this method.

The consequence of adding these different thicknesses of absorption to the plenum was then evaluated by determining the TL through a suspended ceiling system.

The TL through a vertical suspended ceiling was evaluated to determine how much sound was already being lost through the plenum sound path without absorption in the plenum. This was completed on a large vertically mounted suspended ceiling grid at the University of Canterbury. The TL results from these measurements were doubled (as the sound through the plenum sound path travels through the suspended ceiling system twice), and compared to the CFN facility results.

The TL through the plenum sound path was then determined for each ceiling tile product without absorption added to the plenum. This was compared to the results of the TL facility measurements doubled. In all cases, the TL measured through the plenum sound path was higher than the doubled TL from the TL facility, showing sound dissipates as it travels through the plenum.

15 mm, 25 mm, 40 mm, and 100 mm absorption was added in turn over the suspended ceiling system in the CFN facility to determine the effect that absorption in the plenum played in the TL of the plenum sound path. It was seen that the increase in TL was mostly from the additional mass of the absorption product. An increase over that predicted by mass law (6 dB per doubling of surface density) is seen that is attributed to the additional absorption in the plenum.

10.3 Further work

10.3.1 Absorption

There is scope for further investigations into the material properties of mineral fibre (such as tortuosity, shear resistance, characteristic fibre length, porosity, and flow resistance), to provide a better understanding of the sound absorption performance of the product. A more detailed theoretical prediction model could be developed possibly using Allard's model, and modified, if required, for the more dense mineral fibre.

10.3.2 TL of a suspended ceiling

There is currently no model that predicts the performance of a suspended ceiling system (when sound travels through it in one direction only). All current TL models predict the performance of a single or double panel wall system, but due to the flanking through the suspended ceiling grid, these models are not expected to accurately predict the performance of a suspended ceiling system. A TL model could be usefully developed that accurately predicts the TL of a suspended ceiling system.

10.3.3 CFN facility

The performance of the CFN facility could be investigated further by participating in a series of round robin tests. A standard ceiling tile could be tested according to the test method outlined in ASTM E1414-11a in several laboratories to give further confidence in the measured results in the CFN facility developed in this work.

The relationship between the TL of the plenum sound path and absorption in the plenum could be further explored taking into consideration the reverberation time of the plenum itself. Reverberation time measurements in the plenum could be undertaken to find how the average surface absorption coefficients in the plenum affect the TL.

As the plenum is generally a large squat space, sound propagation through the plenum would need to be investigated before any empirical model can be used to determine the TL of the plenum sound path. Sound transmission from the source room into the plenum could also be explored during this study.

There is currently no plenum sound path TL model that accurately predicts the TL of sound through the plenum sound path. While a more in-depth analysis is required on the TL of a suspended ceiling system, absorption in the plenum, sound propagation through the plenum, and other factors, a model could usefully be developed to predict the performance of the plenum sound path.

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Appendix A – Sound Absorption of Ceiling Tiles

Five ceiling tiles were tested with the front face of the ceiling tile facing the sound field and the rear of the ceiling tile facing the sound field in Mount Type-A. Three ceiling tiles were also tested in mount Type E-400, with the front face facing the sound field. All tests were conducted in direct accordance with ISO 354:2003.

These results in this appendix are given in the following order:

- Mount Type-A with the front face facing the sound field
    - AMF Thermatex Silence
    - Armstrong Ultima
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

- Mount Type-A with the back face facing the sound field
    - AMF Thermatex Silence
    - Armstrong Ultima
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

- Mount Type-E with the front face facing the sound field
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

Please note that these results shown in this appendix are averages over multiple tests. For simplicity, the reverberation times, absorption coefficients, and other environmental parameters given in these test logs are the average over the multiple tests conducted rather than all five tests given.

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

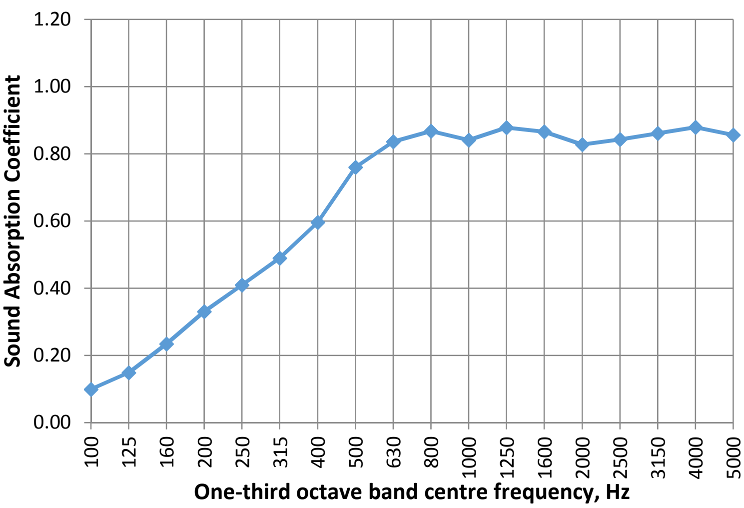
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: T&R CMax Combo 35
Description of specimen: 10 mm plasterboard back
25 mm glass fibre absorption front
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.38	5.45	0.10
125	6.08	4.92	0.15
160	6.87	4.83	0.23
200	7.62	4.65	0.33
250	8.45	4.44	0.41
315	8.24	3.99	0.49
400	7.77	3.51	0.60
500	7.05	2.94	0.76
630	6.10	2.60	0.84
800	5.86	2.51	0.87
1,000	5.62	2.51	0.84
1250	5.18	2.36	0.88
1,600	4.44	2.21	0.87
2,000	4.22	2.20	0.83
2,500	4.01	2.12	0.84
3,150	3.59	1.98	0.86
4,000	3.14	1.82	0.88
5,000	2.62	1.65	0.86



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.15
250	0.40
500	0.75
1,000	0.85
2,000	0.85
4,000	0.85

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.70 MH
Sound absorption class: C
Sound absorption average according to ASTM C423-09a: 0.70

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

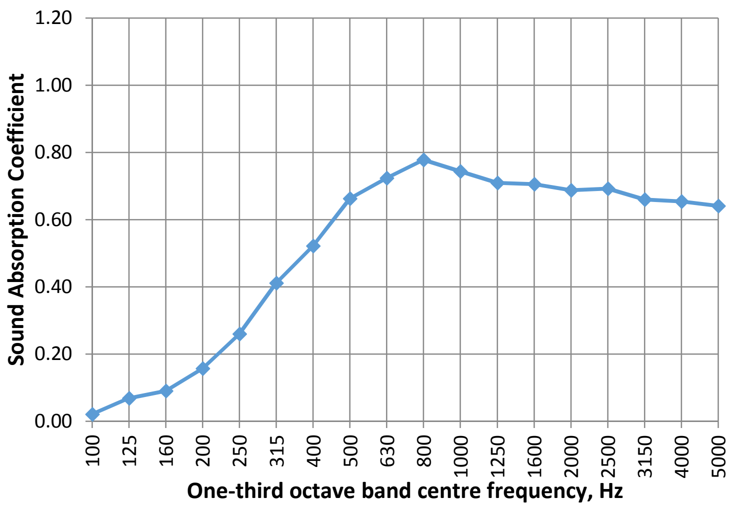
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Armstrong Ultima
Description of specimen: 19 mm mineral fibre back
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.21	5.92	0.02
125	6.54	5.74	0.07
160	7.21	6.00	0.09
200	7.67	5.64	0.16
250	8.39	5.06	0.26
315	8.35	4.06	0.41
400	8.07	3.52	0.52
500	7.47	2.96	0.66
630	6.42	2.64	0.72
800	6.24	2.50	0.78
1,000	5.88	2.50	0.74
1250	5.19	2.43	0.71
1,600	4.48	2.27	0.71
2,000	4.20	2.22	0.69
2,500	4.07	2.18	0.69
3,150	3.56	2.06	0.66
4,000	3.09	1.90	0.65
5,000	2.49	1.67	0.64



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.05
250	0.30
500	0.65
1,000	0.75
2,000	0.70
4,000	0.65

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.6 MH
Sound absorption class: C
Sound absorption average according to ASTM C423-09a: 0.6

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

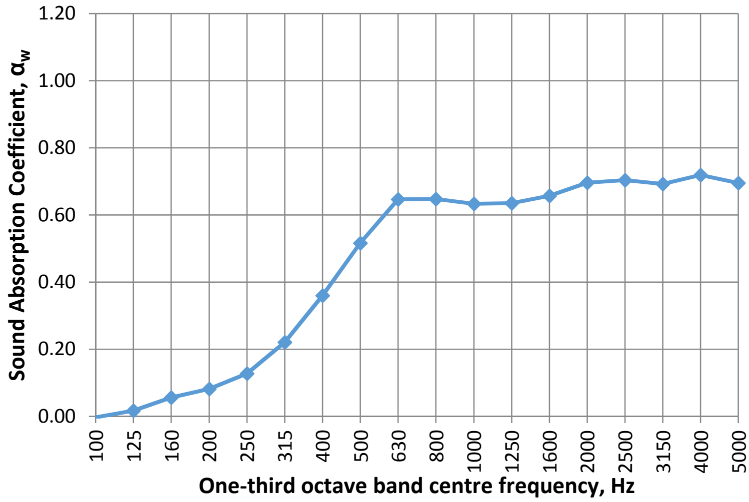
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm mineral fibre with painted white exposed face
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	5.86	5.89	0.00
125	5.94	5.76	0.02
160	6.90	6.15	0.06
200	7.59	6.37	0.08
250	8.35	6.30	0.13
315	8.30	5.28	0.22
400	7.89	4.21	0.36
500	7.18	3.36	0.52
630	6.23	2.77	0.65
800	5.87	2.71	0.65
1,000	5.68	2.69	0.63
1250	5.18	2.57	0.64
1,600	4.45	2.34	0.66
2,000	4.28	2.21	0.70
2,500	4.01	2.14	0.70
3,150	3.55	2.02	0.69
4,000	3.13	1.84	0.72
5,000	2.62	1.67	0.70



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.00
250	0.15
500	0.50
1,000	0.65
2,000	0.70
4,000	0.70

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.5
Sound absorption class: D
Sound absorption average according to ASTM C423-09a: 0.5

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

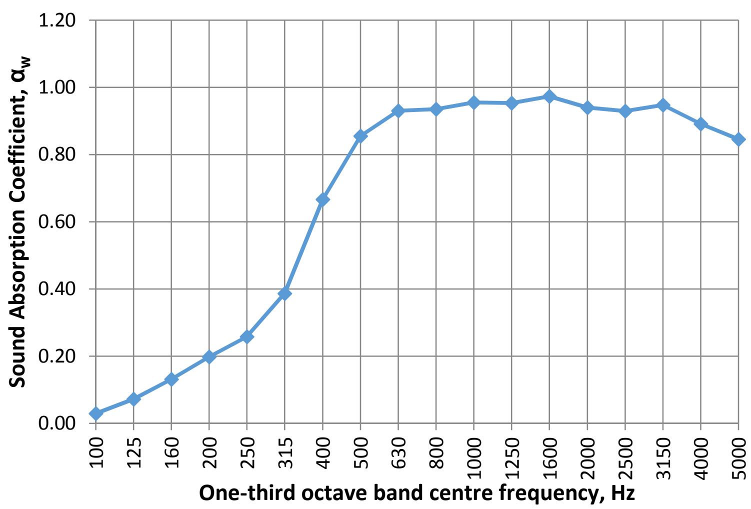
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: T&R CMax Combo 35
Description of specimen: 10 mm plasterboard back
25 mm glass fibre absorption front
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	5.81	5.48	0.03
125	6.34	5.57	0.07
160	7.15	5.56	0.13
200	7.59	5.22	0.20
250	8.56	5.16	0.26
315	8.12	4.21	0.39
400	8.07	3.04	0.67
500	7.63	2.53	0.86
630	6.56	2.28	0.93
800	6.13	2.21	0.94
1,000	5.99	2.16	0.96
1250	5.44	2.09	0.95
1,600	4.63	2.01	0.97
2,000	4.32	1.99	0.94
2,500	4.09	1.95	0.93
3,150	3.62	1.85	0.95
4,000	3.12	1.76	0.89
5,000	2.53	1.59	0.85



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.10
250	0.30
500	0.80
1,000	0.95
2,000	0.95
4,000	0.90

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.75 MH
Sound absorption class: C
Sound absorption average according to ASTM C423-09a: 0.75

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

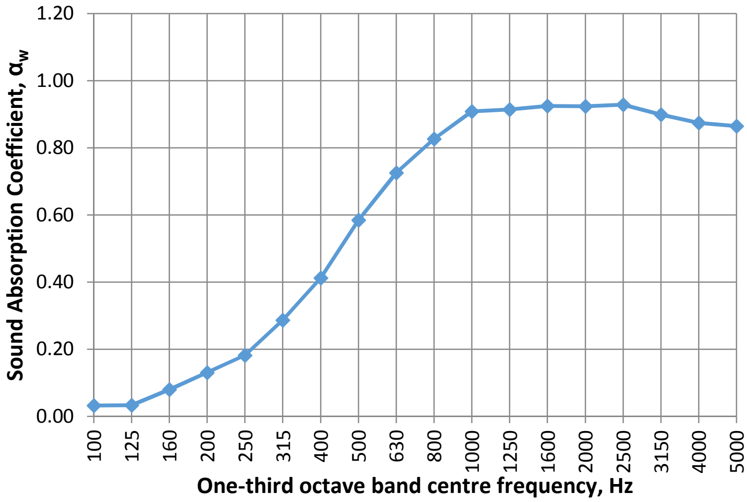
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm mineral fibre absorption backing
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.03	5.66	0.03
125	5.98	5.63	0.03
160	6.89	5.87	0.08
200	7.59	5.81	0.13
250	8.36	5.71	0.18
315	8.34	4.79	0.29
400	7.84	3.93	0.41
500	7.21	3.14	0.58
630	6.17	2.59	0.73
800	5.98	2.37	0.83
1,000	5.69	2.19	0.91
1250	5.19	2.11	0.91
1,600	4.49	1.97	0.92
2,000	4.25	1.92	0.92
2,500	4.00	1.86	0.93
3,150	3.59	1.80	0.90
4,000	3.11	1.69	0.87
5,000	2.59	1.53	0.86



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.05
250	0.20
500	0.55
1,000	0.90
2,000	0.95
4,000	0.90

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.65 MH
Sound absorption class: D
Sound absorption average according to ASTM C423-09a: 0.65

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

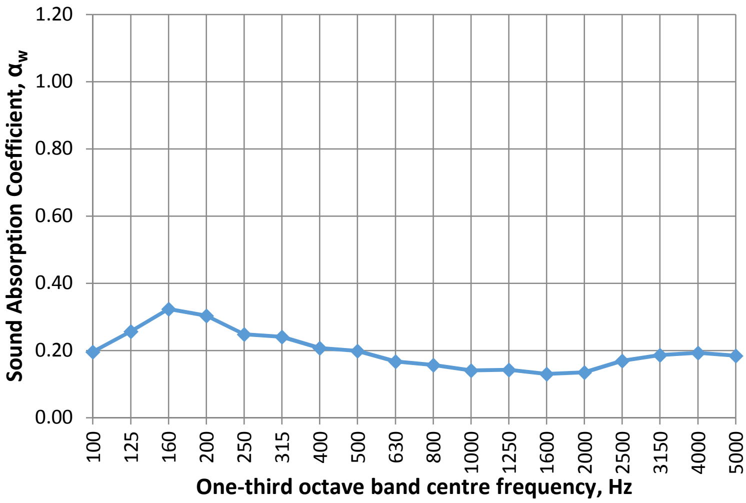
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence
Description of specimen: 13 mm dense mineral fibre back
30 mm mineral fibre absorption front
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.38	4.94	0.20
125	6.08	4.44	0.26
160	6.87	4.48	0.32
200	7.62	4.93	0.30
250	8.45	5.66	0.25
315	8.24	5.61	0.24
400	7.77	5.66	0.21
500	7.05	5.34	0.20
630	6.10	4.95	0.17
800	5.86	4.87	0.16
1,000	5.62	4.80	0.14
1250	5.18	4.46	0.14
1,600	4.44	3.95	0.13
2,000	4.22	3.76	0.13
2,500	4.01	3.48	0.17
3,150	3.59	3.11	0.19
4,000	3.14	2.76	0.19
5,000	2.62	2.36	0.18



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.25
250	0.25
500	0.20
1,000	0.15
2,000	0.15
4,000	0.20

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.20
Sound absorption class: -
Sound absorption average according to ASTM C423-09a: 0.20

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

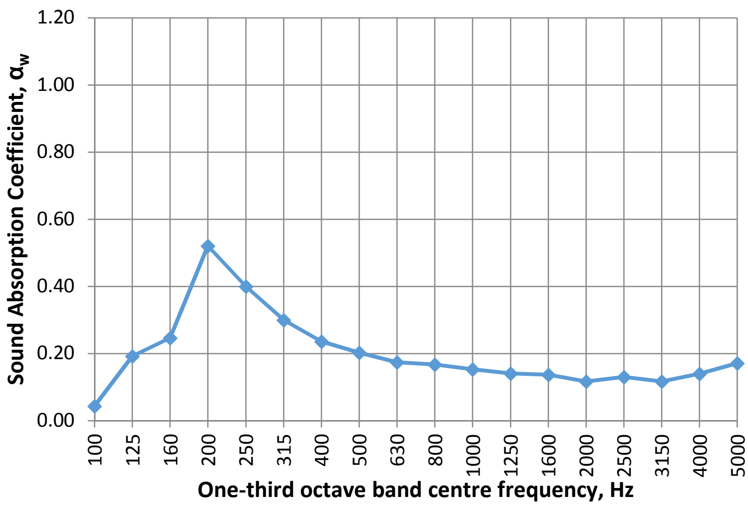
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Armstrong Ultima
Description of specimen: 19 mm mineral fibre absorption back
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.21	5.68	0.04
125	6.54	4.72	0.19
160	7.21	4.66	0.25
200	7.67	3.48	0.52
250	8.39	4.12	0.40
315	8.35	4.71	0.30
400	8.07	5.10	0.24
500	7.47	5.10	0.20
630	6.42	4.77	0.17
800	6.24	4.72	0.17
1,000	5.88	4.60	0.15
1250	5.19	4.23	0.14
1,600	4.48	3.77	0.14
2,000	4.20	3.65	0.12
2,500	4.07	3.50	0.13
3,150	3.56	3.15	0.12
4,000	3.09	2.73	0.14
5,000	2.49	2.20	0.17



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.15
250	0.40
500	0.20
1,000	0.15
2,000	0.15
4,000	0.15

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.20
Sound absorption class: -
Sound absorption average according to ASTM C423-09a: 0.20

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

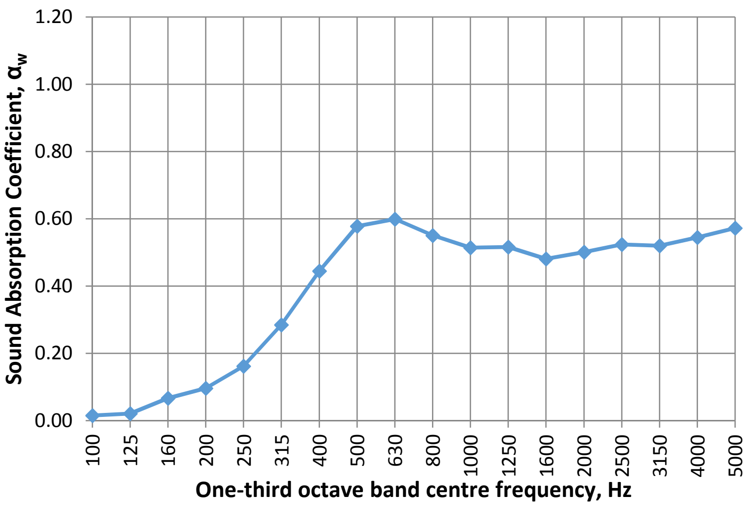
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm mineral fibre absorption back, painted front face
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	5.86	5.69	0.02
125	5.94	5.71	0.02
160	6.90	6.04	0.07
200	7.59	6.19	0.10
250	8.35	5.90	0.16
315	8.30	4.78	0.29
400	7.89	3.79	0.44
500	7.18	3.15	0.58
630	6.23	2.89	0.60
800	5.87	2.94	0.55
1,000	5.68	2.99	0.51
1250	5.18	2.84	0.52
1,600	4.45	2.68	0.48
2,000	4.22	2.55	0.50
2,500	4.01	2.43	0.52
3,150	3.55	2.26	0.52
4,000	3.13	2.05	0.54
5,000	2.62	1.79	0.57



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.05
250	0.20
500	0.55
1,000	0.55
2,000	0.50
4,000	0.55

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.40
Sound absorption class: -
Sound absorption average according to ASTM C423-09a: 0.45

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

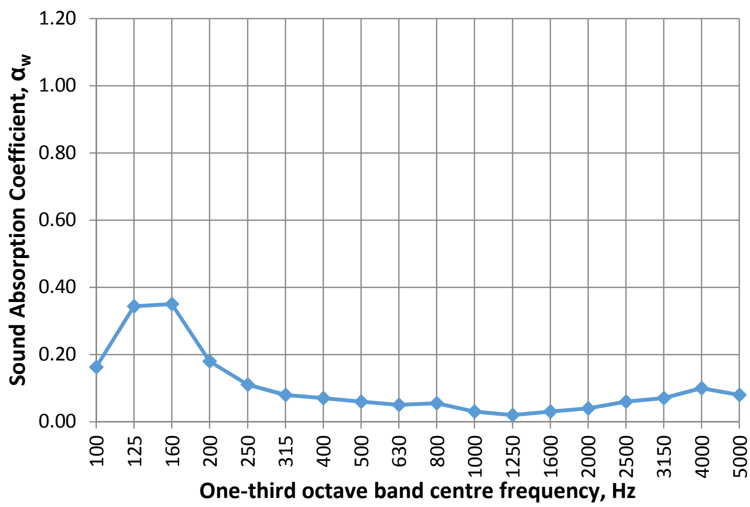
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: T&R CMax Combo 35
Description of specimen: 10 mm plasterboard back
25 mm glass fibre absorption front
White glass fibre tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	5.81	4.62	0.16
125	6.34	3.81	0.34
160	7.15	3.76	0.35
200	7.59	4.31	0.18
250	8.56	4.99	0.11
315	8.12	5.13	0.08
400	8.07	5.38	0.07
500	7.63	5.40	0.06
630	6.56	4.81	0.05
800	6.13	4.92	0.06
1,000	5.99	4.72	0.03
1250	5.44	4.44	0.02
1,600	4.63	4.07	0.03
2,000	4.32	3.92	0.04
2,500	4.09	3.72	0.06
3,150	3.62	3.32	0.07
4,000	3.12	2.90	0.10
5,000	2.53	2.47	0.08



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.30
250	0.10
500	0.05
1,000	0.05
2,000	0.05
4,000	0.10

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.05
Sound absorption class: -
Sound absorption average according to ASTM C423-09a: 0.05

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

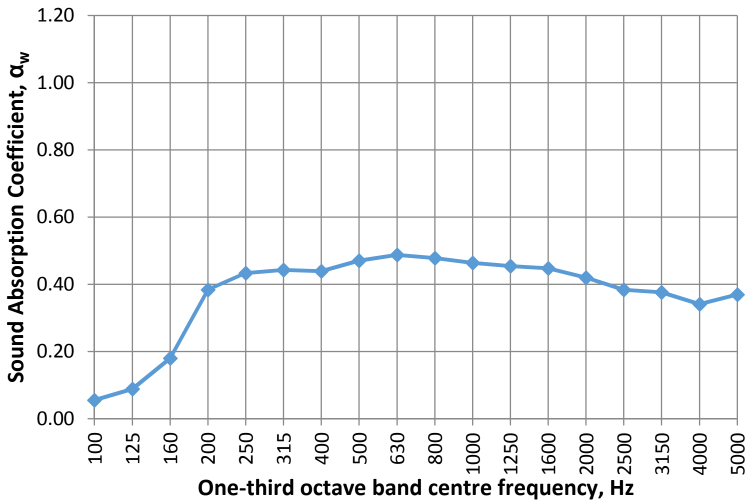
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm mineral fibre absorption back
White glass fibre tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.03	5.45	0.06
125	5.98	5.15	0.09
160	6.89	4.98	0.18
200	7.59	4.04	0.38
250	8.36	3.96	0.43
315	8.34	3.90	0.44
400	7.84	3.81	0.44
500	7.21	3.53	0.47
630	6.17	3.19	0.49
800	5.98	3.17	0.48
1,000	5.69	3.14	0.46
1250	5.19	3.00	0.45
1,600	4.49	2.77	0.45
2,000	4.25	2.73	0.42
2,500	4.00	2.71	0.38
3,150	3.59	2.53	0.38
4,000	3.11	2.34	0.34
5,000	2.59	1.99	0.37



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.10
250	0.40
500	0.45
1,000	0.45
2,000	0.40
4,000	0.35

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.45
Sound absorption class: -
Sound absorption average according to ASTM C423-09a: 0.45

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

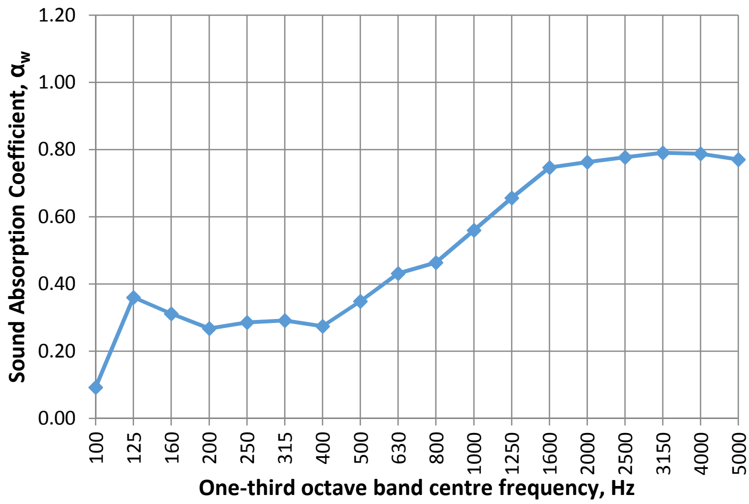
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm mineral fibre absorption back, painted front facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type E-400 according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^oC):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	5.61	4.85	0.09
125	5.77	3.52	0.36
160	6.24	3.90	0.31
200	7.28	4.54	0.27
250	7.92	4.66	0.29
315	8.09	4.65	0.29
400	7.81	4.68	0.28
500	7.24	4.06	0.35
630	6.20	3.39	0.43
800	5.88	3.18	0.46
1,000	5.66	2.85	0.56
1250	5.19	2.52	0.66
1,600	4.50	2.20	0.75
2,000	4.33	2.14	0.76
2,500	4.13	2.07	0.78
3,150	3.66	1.93	0.79
4,000	3.23	1.80	0.79
5,000	2.70	1.64	0.77



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.25
250	0.30
500	0.35
1,000	0.55
2,000	0.75
4,000	0.80

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.50 MH
Sound absorption class: -
Sound absorption average according to ASTM C423-09a: 0.50

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

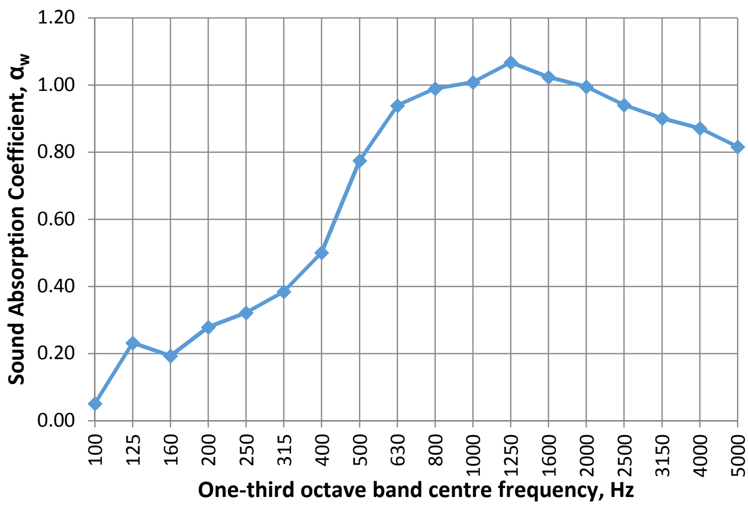
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: T&R CMax Combo 35
Description of specimen: 10 mm plasterboard backing
25 mm glass fibre absorption front
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type E-400 according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	5.67	5.29	0.05
125	5.77	4.10	0.23
160	6.24	4.58	0.19
200	7.28	4.48	0.28
250	7.92	4.43	0.32
315	8.09	4.11	0.38
400	7.81	3.53	0.50
500	7.24	2.66	0.77
630	6.20	2.22	0.94
800	5.88	2.10	0.99
1,000	5.66	2.05	1.01
1250	5.19	1.91	1.07
1,600	4.50	1.85	1.02
2,000	4.33	1.86	0.99
2,500	4.13	1.87	0.94
3,150	3.66	1.81	0.90
4,000	3.23	1.72	0.87
5,000	2.70	1.60	0.82



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.15
250	0.35
500	0.75
1,000	1.00
2,000	1.00
4,000	0.85

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.80 MH
Sound absorption class: B
Sound absorption average according to ASTM C423-09a: 0.80

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

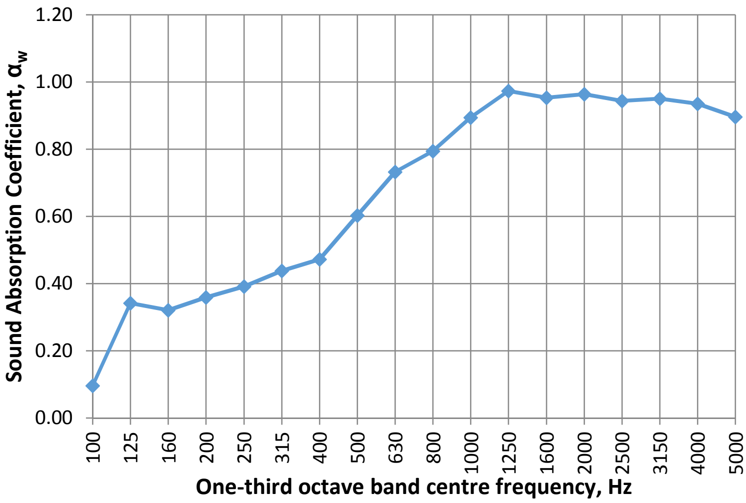
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm mineral fibre absorption back
White glass fibre front tissue facing
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.0 m x 3.6 m – 10.8 m^2
Mount: Mount Type E-400 according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^oC):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	5.61	4.83	0.10
125	5.77	3.58	0.34
160	6.24	3.86	0.32
200	7.28	4.04	0.36
250	7.92	4.06	0.39
315	8.09	3.85	0.44
400	7.81	3.65	0.47
500	7.24	3.09	0.60
630	6.20	2.58	0.73
800	5.88	2.40	0.79
1,000	5.66	2.21	0.89
1250	5.19	2.02	0.97
1,600	4.50	1.93	0.95
2,000	4.33	1.89	0.96
2,500	4.13	1.87	0.94
3,150	3.66	1.76	0.95
4,000	3.23	1.67	0.93
5,000	2.70	1.54	0.90



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.25
250	0.40
500	0.60
1,000	0.90
2,000	0.95
4,000	0.95

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.70 MH
Sound absorption class: C
Sound absorption average according to ASTM C423-09a: 0.70

Appendix B – Sound Absorption of Porous Absorbers

Five glass fibre absorption products were tested in Mount Type-A as described in ISO 354:2003. Four of the absorption products were added to the plenum to determine the effect additional absorption in the cavity. One porous absorber was used for the plenum perimeter walls in the CFN facility. All tests were conducted in direct accordance with ISO 354:2003.

These results in this appendix are given in the following order:

- Porous absorbers for the plenum absorption in Mount Type-A
    - 15 mm glass fibre absorption
    - 25 mm glass fibre absorption
    - 40 mm glass fibre absorption
    - 100 mm glass fibre absorption

- Perimeter plenum absorption for compliance with ASTM E1414-11a
    - 90 mm glass fibre absorption

Please note that these results shown in this appendix are averages over multiple tests. For simplicity, the reverberation times, absorption coefficients, and other environmental parameters given in these test logs are the average over the multiple tests conducted rather than all five tests given.

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

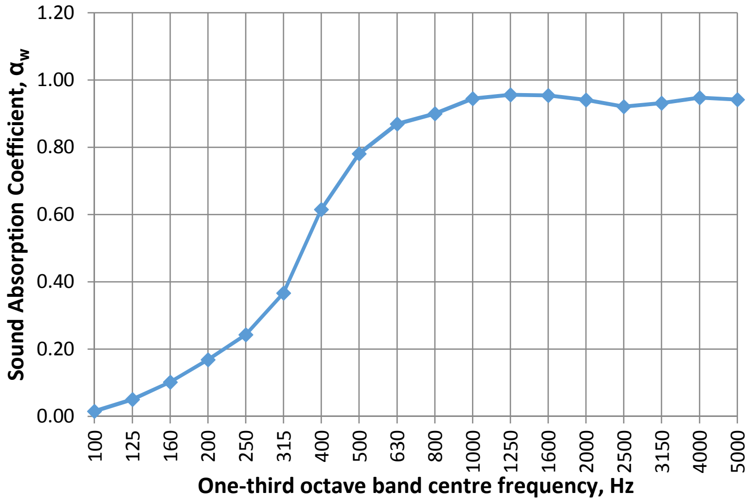
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Absorption for plenum 15 mm thermal insulation
Description of specimen: 15 mm yellow glass fibre thermal insulation
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.6 m x 3.0 m – 11.34 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.03	5.86	0.02
125	8.16	7.24	0.05
160	7.35	5.98	0.10
200	6.96	5.12	0.17
250	7.64	4.87	0.24
315	7.94	4.19	0.37
400	7.49	3.10	0.62
500	7.21	2.64	0.78
630	5.92	2.30	0.87
800	5.62	2.20	0.90
1,000	5.30	2.09	0.95
1250	4.61	1.96	0.96
1,600	4.26	1.89	0.96
2,000	3.94	1.84	0.94
2,500	3.69	1.81	0.92
3,150	3.31	1.70	0.93
4,000	2.87	1.56	0.95
5,000	2.43	1.43	0.94



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.05
250	0.25
500	0.75
1,000	0.95
2,000	0.95
4,000	0.95

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.75
Sound absorption class: C
Sound absorption average according to ASTM C423-09a: 0.75

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

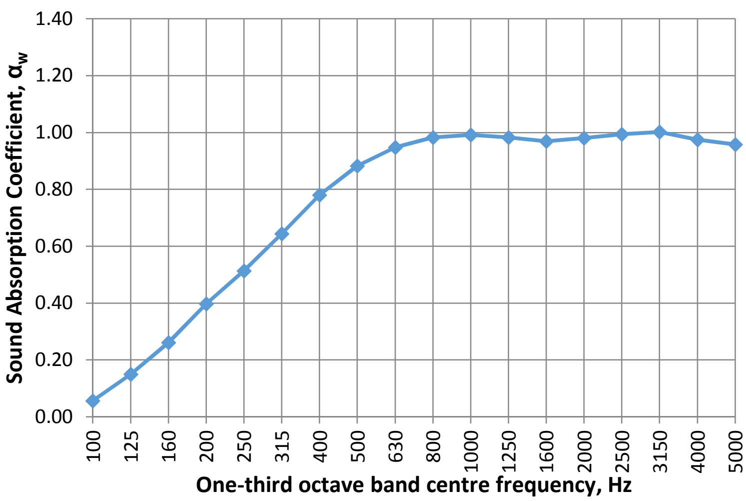
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Absorption for plenum 25 mm thermal insulation
Description of specimen: 25 mm yellow glass fibre thermal insulation
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.6 m x 3.0 m – 11.34 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.03	5.46	0.06
125	8.16	5.94	0.15
160	7.35	4.63	0.26
200	6.96	3.77	0.40
250	7.64	3.47	0.51
315	7.94	3.09	0.64
400	7.49	2.68	0.78
500	7.21	2.44	0.88
630	5.92	2.18	0.95
800	5.62	2.09	0.98
1,000	5.30	2.03	0.99
1250	4.61	1.93	0.98
1,600	4.26	1.88	0.97
2,000	3.94	1.80	0.98
2,500	3.69	1.74	0.99
3,150	3.31	1.64	1.00
4,000	2.87	1.54	0.98
5,000	2.43	1.42	0.96



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.15
250	0.50
500	0.85
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.85
Sound absorption class: B
Sound absorption average according to ASTM C423-09a: 0.85

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

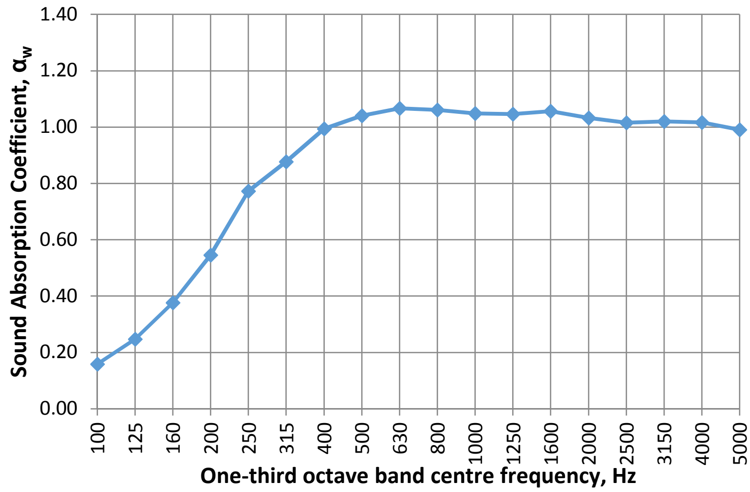
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Absorption for plenum 40 mm thermal insulation
Description of specimen: 40 mm yellow glass fibre thermal insulation
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m³
Area of test specimen: 3.6 m x 3.0 m – 11.34 m²
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.03	4.663	0.16
125	8.16	5.038	0.25
160	7.35	3.979	0.38
200	6.96	3.215	0.55
250	7.64	2.717	0.77
315	7.94	2.531	0.88
400	7.49	2.280	0.99
500	7.21	2.183	1.04
630	5.92	2.015	1.07
800	5.62	1.986	1.06
1,000	5.30	1.959	1.05
1250	4.61	1.860	1.05
1,600	4.26	1.790	1.06
2,000	3.94	1.752	1.03
2,500	3.69	1.715	1.02
3,150	3.31	1.625	1.02
4,000	2.87	1.513	1.02
5,000	2.43	1.397	0.99



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.25
250	0.75
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 0.95
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 0.95

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

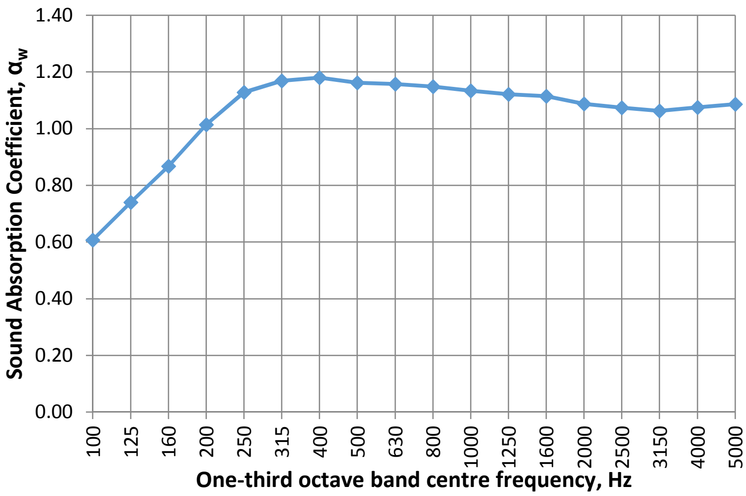
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Absorption for plenum 100 mm thermal insulation
Description of specimen: 100 mm yellow glass fibre thermal insulation
Size of sample: 1200 mm x 600 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 3.6 m x 3.0 m – 10.80 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.03	2.83	0.61
125	8.16	2.86	0.74
160	7.35	2.48	0.87
200	6.96	2.20	1.01
250	7.64	2.09	1.13
315	7.94	2.06	1.17
400	7.49	2.02	1.18
500	7.21	2.01	1.16
630	5.92	1.89	1.16
800	5.62	1.87	1.15
1,000	5.30	1.85	1.13
1250	4.61	1.76	1.12
1,600	4.26	1.71	1.11
2,000	3.94	1.68	1.09
2,500	3.69	1.64	1.07
3,150	3.31	1.56	1.06
4,000	2.87	1.44	1.07
5,000	2.43	1.30	1.09



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.75
250	1.00
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 1.10
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 1.10

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

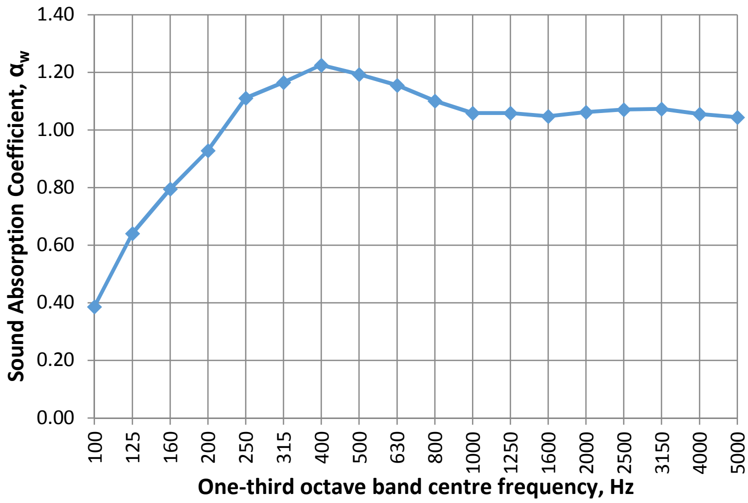
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Pink Batts 90 mm thermal insulation
Description of specimen: 90 mm pink glass fibre thermal insulation
Size of sample: 2400 mm x 1200 mm

Test information: Reverberation Room at the University of Canterbury
Volume: 217 m^3
Area of test specimen: 2.4 m x 4.8 m – 11.52 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	6.01	3.51	0.39
125	8.13	3.13	0.64
160	7.33	2.63	0.79
200	6.93	2.33	0.93
250	7.62	2.12	1.11
315	7.92	2.07	1.17
400	7.46	1.96	1.23
500	7.07	1.97	1.19
630	5.79	1.90	1.16
800	5.48	1.92	1.10
1,000	5.16	1.93	1.06
1250	4.47	1.82	1.06
1,600	4.12	1.77	1.05
2,000	3.80	1.70	1.06
2,500	3.55	1.64	1.07
3,150	3.17	1.55	1.07
4,000	2.73	1.45	1.06
5,000	2.29	1.32	1.04



Frequency, Hz	Practical sound absorption coefficient (α_p)
250	0.60
250	1.00
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 1.00
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 1.00

Appendix C – TL of Vertical Suspended Ceiling Grid

Five difference ceiling tile products where tested in three different mounts to determine the transmission loss. The transmission loss was measured just through a single ceiling tile, in a small suspended ceiling grid, and through a large suspended ceiling grid. All tests were conducted in direct accordance with the ISO 15186 suite of standards, using the sound intensity technique.

These results in this appendix are given in the following order:

- TL of a single ceiling tile mounted in the small TL facility at the University of Canterbury
    - AMF Thermatex Silence
    - Armstrong Ultima
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

- TL of a small suspended ceiling grid in the small TL facility at the University of Canterbury
    - AMF Thermatex Silence
    - Armstrong Ultima
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

- TL of a large suspended ceiling grid in the large TL facility at the University of Canterbury
    - AMF Thermatex Silence
    - Armstrong Ultima
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

Please note that these results shown in this appendix are averages over multiple tests. For simplicity, the TL and other parameters given in these test logs are the average over the multiple tests conducted rather than all five tests given.

Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence

Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged

Size of sample: 1 ceiling tile – 1200 mm x 600 mm

Mass: 10.8 kg/m^2

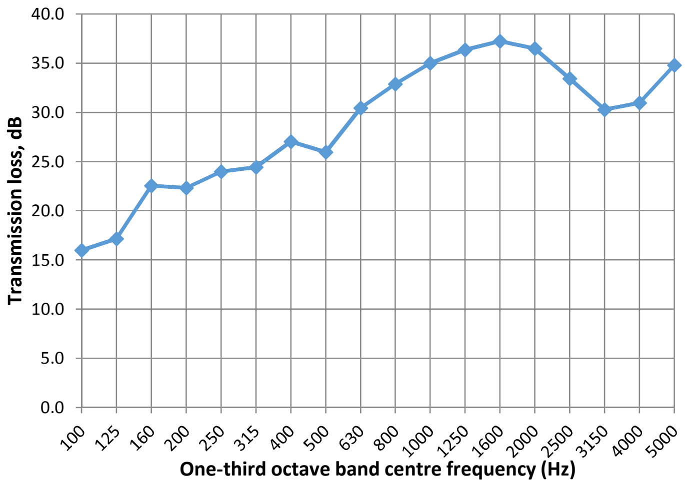
Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury

Volume: Reverberation room: 217 m^3
Small semi anechoic room: 9 m^3

Area of test specimen: 1.1 m x 0.5 m – 0.55 m^2

Mount: Single ceiling tile in vertical frame. Frame gives 10 dB+ attenuation compared to ceiling tile. Frame mounted in opening and torqued evenly.

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	2.08	0.37	16.0
125	1.24	0.30	17.1
160	1.46	0.23	22.5
200	3.04	0.54	22.3
250	4.18	0.10	24.0
315	3.32	0.24	24.4
400	5.59	0.07	27.1
500	7.59	0.27	26.0
630	6.43	0.03	30.5
800	5.85	0.07	32.9
1,000	6.41	0.10	35.0
1250	6.20	0.13	36.4
1,600	6.32	0.10	37.2
2,000	6.65	0.20	36.5
2,500	5.70	0.33	33.4
3,150	4.57	0.27	30.3
4,000	4.41	0.10	31.0
5,000	4.30	0.37	34.8



Frequency, Hz	Practical Transmission Loss (dB)
250	19.6
250	23.7
500	28.3
1,000	35.0
2,000	36.0
4,000	32.5

Transmission Loss:

Weighted sound reduction index in accordance with ISO 717-1:2000: 32

Spectrum adaption, C, C_{tr}: -2, -4

Sound transmission class (STC) in accordance with ASTM E413-10: 32

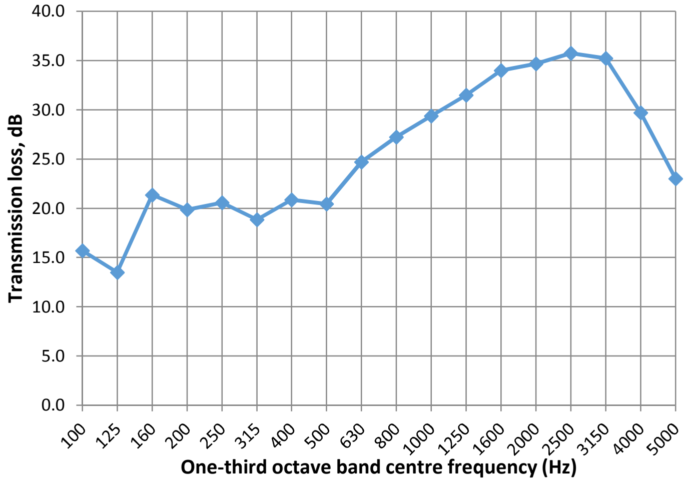
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Armstrong Ultima
Description of specimen: 19 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: 1 ceiling tile – 1200 mm x 600 mm
Mass: 5.2 kg/m²

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m³
Small semi anechoic room: 9 m³
Area of test specimen: 1.1 m x 0.5 m – 0.55 m²
Mount: Single ceiling tile in vertical frame. Frame gives 10 dB+ attenuation compared to ceiling tile. Frame mounted in opening and torqued evenly.

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.54	0.34	15.7
125	1.20	0.31	13.5
160	2.03	0.17	21.3
200	3.60	0.20	19.8
250	3.87	0.23	20.6
315	3.50	0.28	18.8
400	5.53	0.24	20.9
500	7.97	0.27	20.5
630	6.40	0.21	24.7
800	5.90	0.17	27.2
1,000	6.17	0.10	29.4
1250	5.83	0.13	31.5
1,600	6.07	0.13	34.0
2,000	6.53	0.03	34.7
2,500	6.53	0.03	35.8
3,150	5.93	0.07	35.2
4,000	4.97	0.17	29.7
5,000	4.20	0.10	23.0



Frequency, Hz	Practical Transmission Loss (dB)
250	18.1
250	19.8
500	22.5
1,000	29.7
2,000	34.9
4,000	31.7

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 25
Spectrum adaption, C, C_{tr}: 0, -2
Sound transmission class (STC) in accordance with ASTM E413-10: 25

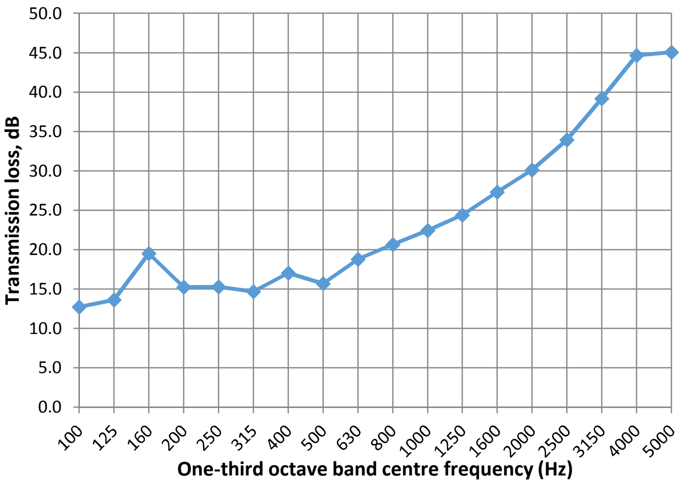
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm porous mineral fibre absorption layer
White painted facing with
Square edged
Size of sample: 1 ceiling tile – 1200 mm x 600 mm
Mass: 5.2 kg/m²

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m³
Small semi anechoic room: 9 m³
Area of test specimen: 1.1 m x 0.5 m – 0.55 m²
Mount: Single ceiling tile in vertical frame. Frame gives 10 dB+ attenuation compared to ceiling tile. Frame mounted in opening and torqued evenly.

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.10	0.17	12.7
125	2.00	0.34	13.6
160	2.63	0.27	19.5
200	3.40	0.34	15.2
250	3.83	0.10	15.3
315	3.67	0.10	14.7
400	5.50	0.17	17.0
500	7.47	0.13	15.7
630	6.27	0.17	18.8
800	5.83	0.03	20.6
1,000	6.00	0.10	22.4
1250	5.67	0.10	24.4
1,600	5.43	0.27	27.3
2,000	5.57	0.13	30.1
2,500	5.13	0.10	33.9
3,150	5.13	0.10	39.2
4,000	5.50	0.13	44.7
5,000	5.83	0.07	45.1



Frequency, Hz	Practical Transmission Loss (dB)
250	16.4
250	15.1
500	17.4
1,000	22.7
2,000	31.3
4,000	43.7

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 18
Spectrum adaption, C, C_{tr}: 0, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 18

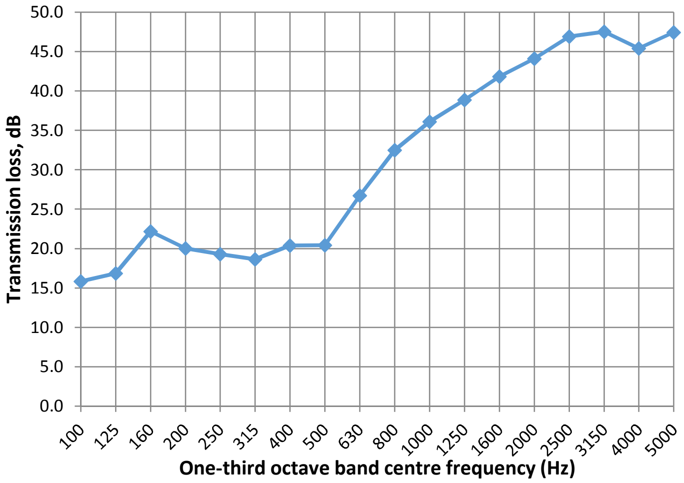
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35
Description of specimen: 10 mm plasterboard back
25 mm porous glass fibre absorption front layer
White glass fibre front tissue facing
Square edged
Size of sample: 1 ceiling tile – 1200 mm x 600 mm
Mass: 10.2 kg/m^2

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m^3
Small semi anechoic room: 9 m^3
Area of test specimen: 1.1 m x 0.5 m – 0.55 m^2
Mount: Single ceiling tile in vertical frame. Frame gives 10 dB+ attenuation compared to ceiling tile. Frame mounted in opening and torqued evenly.

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.58	0.27	15.9
125	2.60	0.40	16.9
160	1.27	0.17	22.2
200	1.84	0.50	20.0
250	4.15	0.17	19.3
315	2.30	0.07	18.7
400	5.44	0.10	20.4
500	8.07	0.13	20.4
630	7.27	0.17	26.7
800	7.47	0.27	32.5
1,000	9.07	0.17	36.1
1250	7.07	0.14	38.9
1,600	7.30	0.13	41.9
2,000	7.61	0.60	44.1
2,500	7.41	0.34	46.9
3,150	7.47	0.10	47.5
4,000	6.94	0.30	45.4
5,000	5.37	0.24	47.4



Frequency, Hz	Practical Transmission Loss (dB)
250	19.2
250	19.4
500	23.6
1,000	36.6
2,000	44.8
4,000	46.9

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 29
Spectrum adaption, C, C_{tr}: -1, -4
Sound transmission class (STC) in accordance with ASTM E413-10: 29

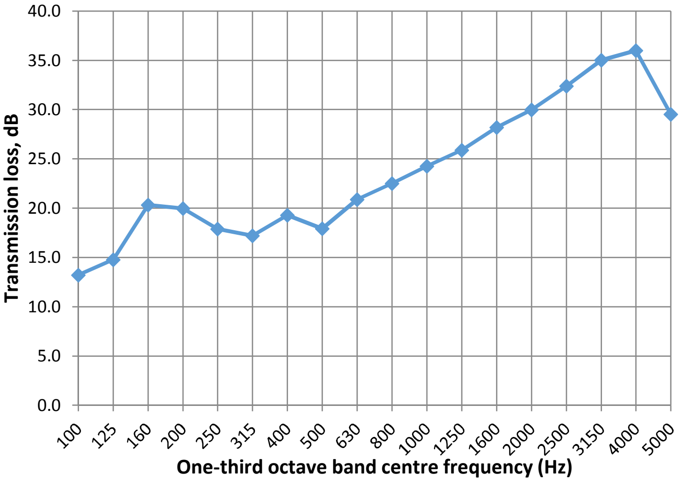
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm porous mineral fibre back layer
White glass fibre front tissue facing
Square edged
Size of sample: 1 ceiling tile – 1200 mm x 600 mm
Mass: 10.2 kg/m²

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m³
Small semi anechoic room: 9 m³
Area of test specimen: 1.1 m x 0.5 m – 0.55 m²
Mount: Single ceiling tile in vertical frame. Frame gives 10 dB+ attenuation compared to ceiling tile. Frame mounted in opening and torqued evenly.

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	2.11	0.52	13.2
125	0.94	0.34	14.8
160	0.33	0.33	20.3
200	1.47	0.27	20.0
250	2.23	0.37	17.9
315	1.70	0.44	17.2
400	3.77	0.37	19.3
500	4.90	0.30	17.9
630	3.70	0.10	20.9
800	3.37	0.20	22.5
1,000	3.40	0.17	24.2
1250	3.27	0.24	25.9
1,600	3.03	0.20	28.2
2,000	2.93	0.34	30.0
2,500	2.70	0.30	32.4
3,150	2.77	0.20	35.0
4,000	3.00	0.13	36.0
5,000	2.83	0.13	29.5



Frequency, Hz	Practical Transmission Loss (dB)
250	17.2
250	18.5
500	19.5
1,000	24.4
2,000	30.5
4,000	34.3

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 25
Spectrum adaption, C, C_{tr}: -1, -2
Sound transmission class (STC) in accordance with ASTM E413-10: 25

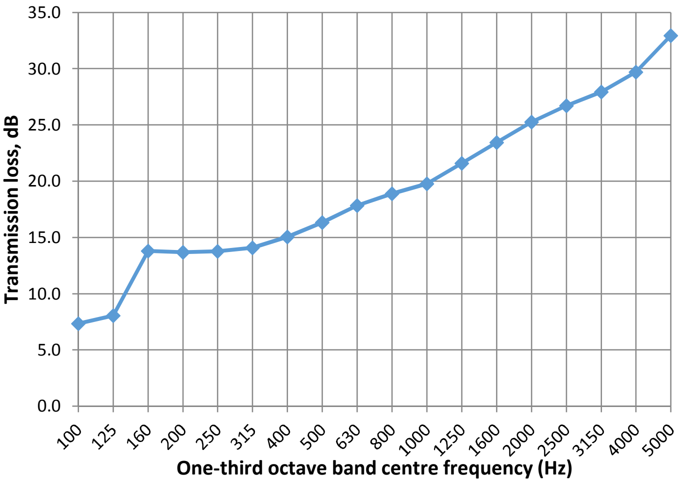
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence
Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: 1 full ceiling tile – 1200 mm x 600 mm, 8 small section
Mass: 10.8 kg/m^2

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m^3
Small semi anechoic room: 9 m^3
Area of test specimen: 1.59 m x 0.95 m – 1.51 m^2
Mount: Small suspended ceiling grid, with one full ceiling tile, 8 small cut-offs. Wall surrounding reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.93	0.50	7.4
125	3.37	0.24	8.1
160	2.24	0.44	13.8
200	2.70	0.57	13.7
250	3.03	0.17	13.8
315	3.40	0.17	14.1
400	3.80	0.24	15.1
500	4.17	0.03	16.3
630	3.77	0.30	17.8
800	3.90	0.20	18.9
1,000	3.83	0.10	19.8
1250	3.70	0.34	21.6
1,600	3.17	0.24	23.4
2,000	3.10	0.20	25.3
2,500	2.87	0.07	26.7
3,150	2.87	0.03	27.9
4,000	3.37	0.13	29.7
5,000	3.80	0.17	32.9



Frequency, Hz	Practical Transmission Loss (dB)
250	10.8
250	13.8
500	16.6
1,000	20.2
2,000	25.3
4,000	30.7

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 21
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 21

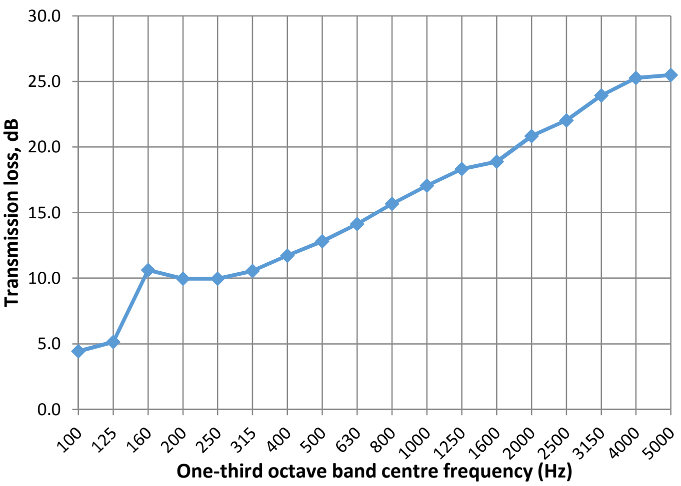
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Armstrong Ultima
Description of specimen: 19 mm porous mineral fibre backing
White glass fibre front tissue facing
Square edged
Size of sample: 1 full ceiling tile – 1200 mm x 600 mm, 8 small section
Mass: 5.2 kg/m^2

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m^3
Small semi anechoic room: 9 m^3
Area of test specimen: 1.59 m x 0.95 m – 1.51 m^2
Mount: Small suspended ceiling grid, with one full ceiling tile, 8 small cut-offs. Wall surrounding reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	4.33	0.14	4.4
125	3.80	0.17	5.1
160	2.30	0.13	10.6
200	4.20	0.17	10.0
250	4.73	0.07	10.0
315	5.07	0.10	10.6
400	5.60	0.31	11.7
500	5.80	0.30	12.8
630	6.00	0.13	14.1
800	6.00	0.07	15.7
1,000	6.40	0.03	17.1
1250	5.80	0.17	18.3
1,600	4.80	0.07	18.9
2,000	5.70	0.24	20.8
2,500	5.43	0.27	22.0
3,150	5.60	0.10	23.9
4,000	5.47	0.20	25.3
5,000	4.17	0.00	25.5



Frequency, Hz	Practical Transmission Loss (dB)
250	7.7
250	10.2
500	13.0
1,000	17.2
2,000	20.8
4,000	25.0

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 18
Spectrum adaption, C, C_{tr}: 0, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 18

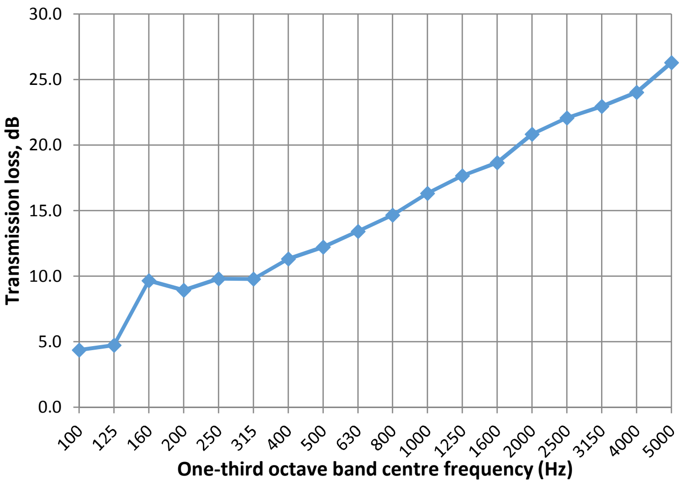
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm mineral fibre absorption back
White painted facing with indentations
Square edged
Size of sample: 1 full ceiling tile – 1200 mm x 600 mm, 8 small section
Mass: 3.3 kg/m²

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m³
Small semi anechoic room: 9 m³
Area of test specimen: 1.59 m x 0.95 m – 1.51 m²
Mount: Small suspended ceiling grid, with one full ceiling tile, 8 small cut-offs. Wall surrounding reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.90	0.70	4.4
125	3.20	0.17	4.7
160	2.27	0.17	9.7
200	3.67	0.20	8.9
250	4.30	0.17	9.8
315	5.13	0.17	9.8
400	5.13	0.03	11.3
500	5.60	0.17	12.2
630	5.53	0.23	13.4
800	5.53	0.33	14.6
1,000	5.37	0.27	16.3
1250	4.80	0.23	17.7
1,600	3.93	0.27	18.7
2,000	4.17	0.53	20.8
2,500	3.83	0.53	22.1
3,150	3.60	0.50	23.0
4,000	4.07	0.67	24.0
5,000	4.03	0.30	26.3



Frequency, Hz	Practical Transmission Loss (dB)
250	7.0
250	9.5
500	12.4
1,000	16.4
2,000	20.7
4,000	24.6

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 17
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 16

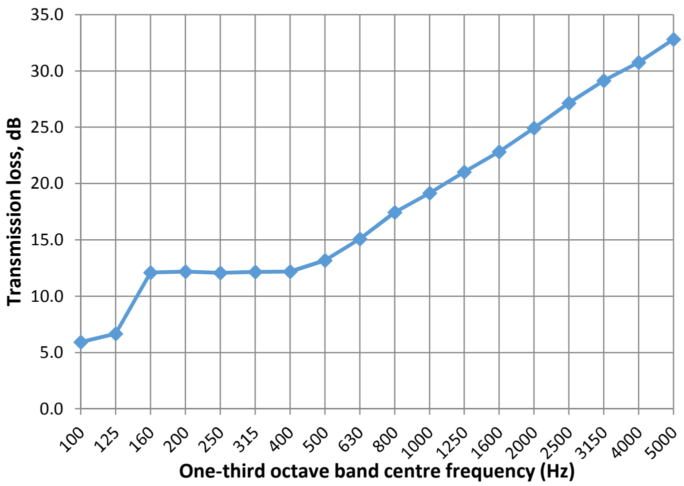
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35
Description of specimen: 10 Plasterboard back
25 mm porous glass fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: 1 full ceiling tile – 1200 mm x 600 mm, 8 small section
Mass: 10.2 kg/m^2

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m^3
Small semi anechoic room: 9 m^3
Area of test specimen: 1.59 m x 0.95 m – 1.51 m^2
Mount: Small suspended ceiling grid, with one full ceiling tile, 8 small cut-offs. Wall surrounding reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	4.00	0.58	5.9
125	3.23	0.34	6.7
160	2.20	0.30	12.1
200	2.67	0.47	12.2
250	3.13	0.27	12.1
315	3.50	0.17	12.1
400	4.04	0.10	12.2
500	4.27	0.14	13.2
630	3.94	0.13	15.1
800	4.04	0.03	17.5
1,000	4.04	0.17	19.1
1250	4.14	0.10	21.0
1,600	3.27	0.34	22.8
2,000	3.64	0.35	24.9
2,500	3.44	0.24	27.1
3,150	3.54	0.14	29.1
4,000	3.80	0.07	30.8
5,000	4.00	0.10	32.8



Frequency, Hz	Practical Transmission Loss (dB)
250	9.2
250	12.1
500	13.7
1,000	19.5
2,000	25.3
4,000	31.2

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 20
Spectrum adaption, C, C_{tr}: -1, -4
Sound transmission class (STC) in accordance with ASTM E413-10: 20

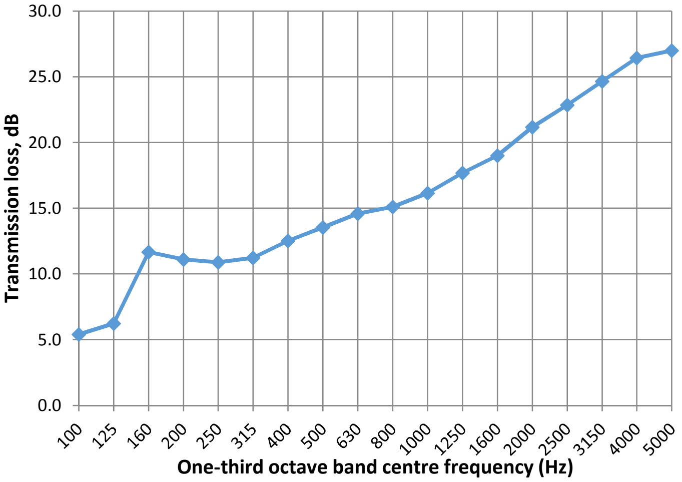
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm mineral fibre absorption back
White glass fibre front tissue facing
Square edged
Size of sample: 1 full ceiling tile – 1200 mm x 600 mm, 8 small section
Mass: 4.7 kg/m²

Test information: Small transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Small semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m³
Small semi anechoic room: 9 m³
Area of test specimen: 1.59 m x 0.95 m – 1.51 m²
Mount: Small suspended ceiling grid, with one full ceiling tile, 8 small cut-offs. Wall surrounding reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.53	0.13	5.4
125	3.10	0.23	6.2
160	2.40	0.20	11.7
200	4.00	0.30	11.1
250	4.43	0.10	10.9
315	5.20	0.13	11.2
400	5.40	0.13	12.5
500	5.67	0.20	13.5
630	5.53	0.03	14.6
800	5.33	0.13	15.1
1,000	5.37	0.17	16.1
1250	4.60	0.17	17.7
1,600	3.83	0.27	19.0
2,000	3.93	0.17	21.2
2,500	3.80	0.27	22.8
3,150	3.93	0.24	24.6
4,000	4.33	0.07	26.4
5,000	4.23	0.10	27.0



Frequency, Hz	Practical Transmission Loss (dB)
250	8.7
250	11.1
500	13.6
1,000	16.4
2,000	21.3
4,000	26.1

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 16
Spectrum adaption, C, C_{tr}: 0, -2
Sound transmission class (STC) in accordance with ASTM E413-10: 16

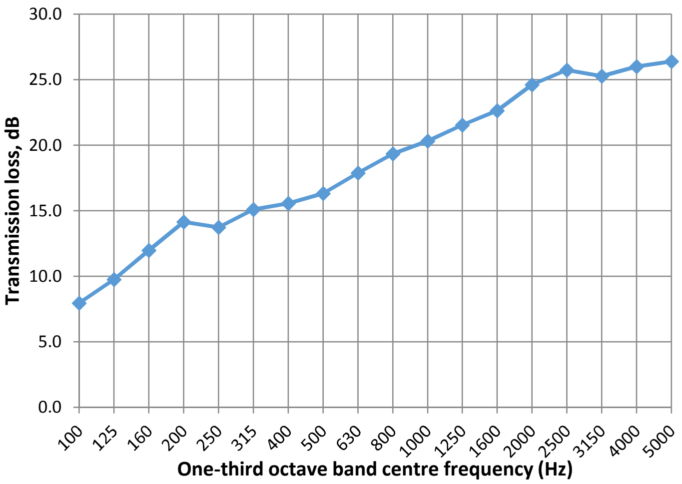
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence
Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: 8 full ceiling tiles – 1200 mm x 600 mm
Mass: 10.8 kg/m²

Test information: Large transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Large semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m³
Small semi anechoic room: 200 m³
Area of test specimen: 2.410 m x 2.405 m – 5.80 m²
Mount: Large suspended ceiling grid, with eight full ceiling tiles. Surrounding wall reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.77	0.27	8.0
125	2.97	0.17	9.8
160	3.77	0.13	12.0
200	3.50	0.17	14.1
250	4.10	0.23	13.7
315	4.77	0.10	15.1
400	4.53	0.14	15.6
500	4.70	0.13	16.3
630	4.73	0.07	17.9
800	4.50	0.17	19.3
1,000	4.23	0.20	20.3
1250	4.30	0.20	21.5
1,600	4.84	0.40	22.6
2,000	5.17	0.37	24.6
2,500	5.00	0.34	25.7
3,150	5.17	0.44	25.3
4,000	4.90	0.72	26.0
5,000	4.54	0.74	26.4



Frequency, Hz	Practical Transmission Loss (dB)
250	10.2
250	14.4
500	16.7
1,000	20.5
2,000	24.5
4,000	25.9

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 22
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 22

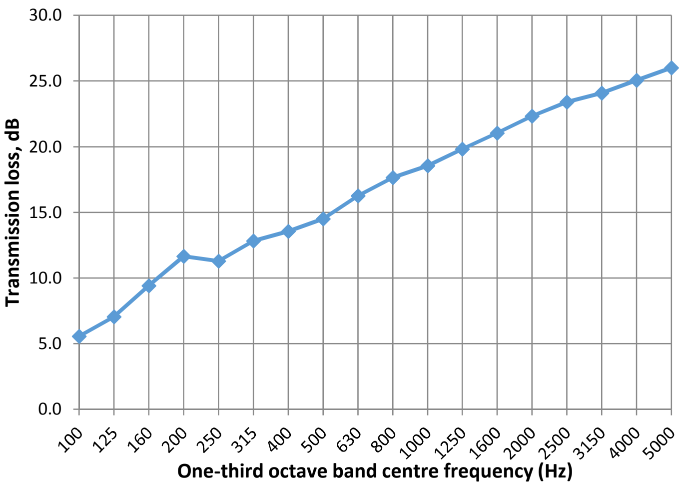
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Armstrong Ultima
Description of specimen: 19 mm mineral fibre absorption backing
White glass fibre front tissue facing
Square edged
Size of sample: 8 full ceiling tiles – 1200 mm x 600 mm
Mass: 5.7 kg/m^2

Test information: Large transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Large semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m^3
Small semi anechoic room: 200 m^3
Area of test specimen: 2.410 m x 2.405 m – 5.80 m^2
Mount: Large suspended ceiling grid, with eight full ceiling tiles. Surrounding wall reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.30	0.30	5.6
125	2.80	0.14	7.1
160	3.57	0.07	9.4
200	3.40	0.20	11.6
250	4.07	0.13	11.3
315	4.50	0.17	12.8
400	4.30	0.13	13.6
500	4.67	0.10	14.5
630	4.83	0.13	16.3
800	4.73	0.07	17.6
1,000	4.63	0.07	18.5
1250	4.53	0.13	19.8
1,600	4.87	0.20	21.0
2,000	4.90	0.10	22.3
2,500	4.67	0.20	23.4
3,150	4.60	0.24	24.1
4,000	4.17	0.13	25.1
5,000	3.93	0.03	26.0



Frequency, Hz	Practical Transmission Loss (dB)
250	7.6
250	12.0
500	14.9
1,000	18.8
2,000	22.4
4,000	25.1

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 19
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 19

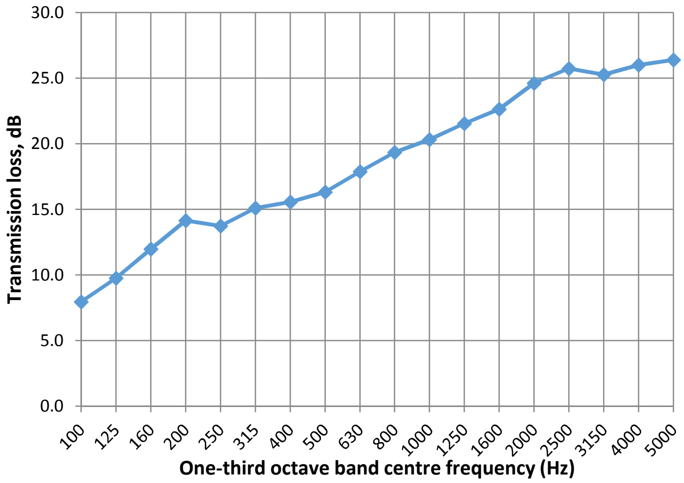
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35
Description of specimen: 10 mm plasterboard backing
25 mm glass fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: 8 full ceiling tiles – 1200 mm x 600 mm
Mass: 10.2 kg/m^2

Test information: Large transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Large semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m^3
Small semi anechoic room: 200 m^3
Area of test specimen: 2.410 m x 2.405 m – 5.80 m^2
Mount: Large suspended ceiling grid, with eight full ceiling tiles. Surrounding wall reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.47	0.24	7.6
125	2.97	0.47	9.3
160	3.67	0.20	11.5
200	3.37	0.17	13.4
250	4.07	0.20	12.6
315	4.80	0.07	13.4
400	4.50	0.20	13.9
500	4.80	0.24	15.7
630	4.70	0.27	18.3
800	4.50	0.20	20.4
1,000	4.23	0.27	21.5
1250	4.53	0.27	22.7
1,600	5.40	0.27	23.5
2,000	5.77	0.35	25.8
2,500	5.43	0.35	27.3
3,150	5.67	0.44	26.9
4,000	5.40	0.58	27.3
5,000	5.10	0.45	27.2



Frequency, Hz	Practical Transmission Loss (dB)
250	9.7
250	13.2
500	16.3
1,000	21.6
2,000	25.8
4,000	27.1

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 21
Spectrum adaption, C, C_{tr}: -1, -4
Sound transmission class (STC) in accordance with ASTM E413-10: 21

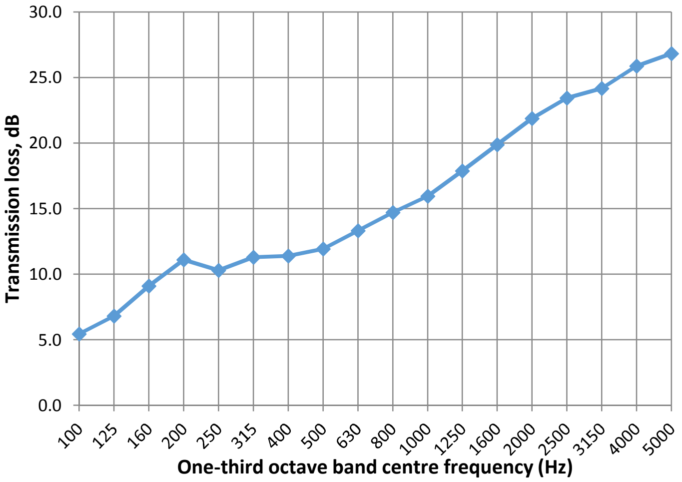
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm porous mineral fibre absorption layer
Painted white facing with indentations
Square edged
Size of sample: 8 full ceiling tiles – 1200 mm x 600 mm
Mass: 3.3 kg/m²

Test information: Large transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Large semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m³
Small semi anechoic room: 200 m³
Area of test specimen: 2.410 m x 2.405 m – 5.80 m²
Mount: Large suspended ceiling grid, with eight full ceiling tiles. Surrounding wall reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.37	0.24	5.5
125	2.73	0.40	6.8
160	3.47	0.33	9.1
200	3.20	0.10	11.1
250	3.97	0.17	10.3
315	4.40	0.03	11.3
400	4.17	0.33	11.4
500	4.60	0.13	11.9
630	4.83	0.23	13.3
800	5.00	0.30	14.7
1,000	5.00	0.24	16.0
1250	4.80	0.17	17.9
1,600	4.73	0.20	19.9
2,000	4.33	0.17	21.9
2,500	3.67	0.33	23.4
3,150	3.13	0.51	24.2
4,000	3.23	0.61	25.9
5,000	3.44	0.85	26.8



Frequency, Hz	Practical Transmission Loss (dB)
250	7.4
250	10.9
500	12.3
1,000	16.4
2,000	22.0
4,000	25.8

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 16
Spectrum adaption, C, C_{tr}: 0, -2
Sound transmission class (STC) in accordance with ASTM E413-10: 17

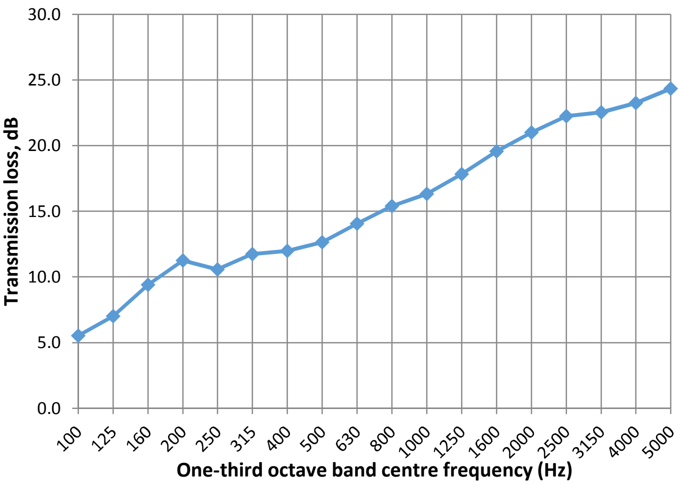
Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: 8 full ceiling tiles – 1200 mm x 600 mm
Mass: 4.7 kg/m^2

Test information: Large transmission suite at the University of Canterbury
Reverberation room at the University of Canterbury
Large semi anechoic room at the University of Canterbury
Volume: Reverberation room: 217 m^3
Small semi anechoic room: 200 m^3
Area of test specimen: 2.410 m x 2.405 m – 5.80 m^2
Mount: Large suspended ceiling grid, with eight full ceiling tiles. Surrounding wall reduces sound by 10 dB+ than through suspended ceiling

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.37	0.20	5.5
125	2.77	0.24	7.0
160	3.47	0.03	9.4
200	3.27	0.30	11.2
250	3.90	0.20	10.6
315	4.53	0.03	11.7
400	4.30	0.33	12.0
500	4.63	0.23	12.6
630	4.77	0.23	14.0
800	4.63	0.30	15.4
1,000	4.40	0.34	16.3
1250	4.20	0.24	17.8
1,600	4.33	0.23	19.6
2,000	4.23	0.23	21.0
2,500	4.00	0.20	22.3
3,150	3.97	0.10	22.5
4,000	4.11	0.23	23.2
5,000	3.83	0.13	24.3



Frequency, Hz	Practical Transmission Loss (dB)
250	7.6
250	11.2
500	13.0
1,000	16.6
2,000	21.1
4,000	23.4

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 16
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 16

Appendix D – TL of the Plenum Sound Path

Four difference ceiling tile products were tested with five different thicknesses of absorption in the plenum, no absorption, 15 mm, 25 mm, 40 mm, and 100 mm. The transmission loss through the plenum sound path was measured in direct accordance with ASTM E1414-11a.

These results in this appendix are given in the following order:

- TL through the plenum sound path with no of absorption in the plenum
    - AMF Thermatex Silence
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars
- TL through the plenum sound path with 15 mm of absorption in the plenum
    - AMF Thermatex Silence
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars
- TL through the plenum sound path with 25 mm of absorption in the plenum
    - AMF Thermatex Silence
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars
- TL through the plenum sound path with 40 mm of absorption in the plenum
    - AMF Thermatex Silence
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

- TL through the plenum sound path with 100 mm of absorption in the plenum
    - AMF Thermatex Silence
    - Daiken New NDF
    - T&R Interior Systems CMax Combo 35
    - USG Mars

Please note that these results shown in this appendix are averages over multiple tests. For simplicity, the reverberation times, absorption coefficients, and other environmental parameters given in these test logs are the average over the multiple tests conducted rather than all five tests given.

Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence

Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged

Size of sample: Full ceiling -

Mass: 10.8 kg/m^2

Suspended ceiling grid: USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury

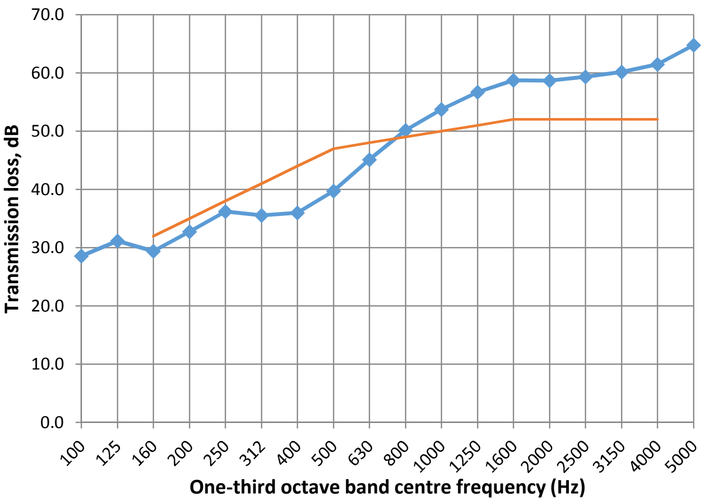
Volume: Source Room – 46.13 m^2
Receiving room – 46.66 m^2

Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61

Area of test specimen: 7.1 m x 4.5 m – 31.95 m^2

Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	74.2	40.8	28.6
125	84.1	48.7	31.2
160	87.6	54.9	29.4
200	91.8	55.6	32.7
250	94.0	54.0	36.2
315	93.5	53.9	35.6
400	89.8	50.1	36.0
500	88.5	45.3	39.7
630	87.7	38.8	45.1
800	89.3	35.6	50.1
1,000	89.2	31.9	53.7
1250	89.2	29.1	56.7
1,600	90.8	29.8	58.7
2,000	91.5	29.9	58.7
2,500	91.2	29.3	59.3
3,150	89.2	27.0	60.2
4,000	87.6	23.9	61.5
5,000	86.9	19.3	64.8



Frequency, Hz	Practical Flanking noise (dB)
250	29.9
250	35.1
500	41.8
1,000	54.3
2,000	58.9
4,000	62.6

Transmission Loss:

Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 48

Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 48

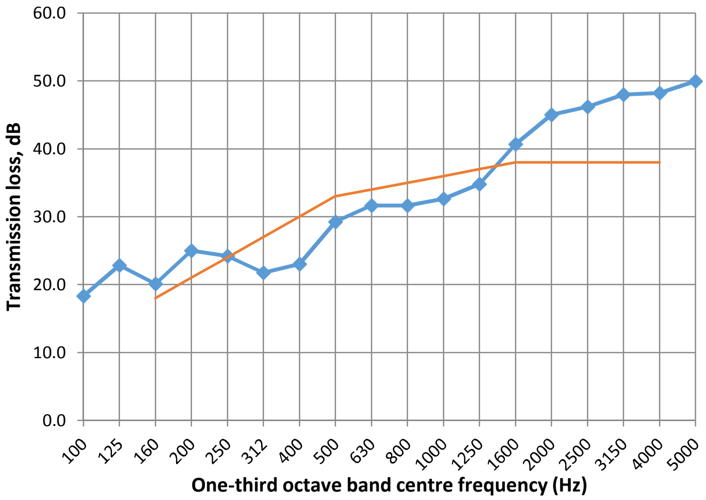
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm porous mineral fibre absorption layer
White painted facing with indentations
Square edged
Size of sample: Full ceiling -
Mass: 3.3 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	73.2	50.1	18.3
125	84.2	56.9	22.9
160	87.1	64.4	20.1
200	92.5	64.8	25.0
250	95.0	68.1	24.2
315	93.8	69.6	21.8
400	92.6	67.3	23.0
500	91.9	59.9	29.3
630	90.3	55.7	31.6
800	91.1	56.2	31.6
1,000	91.0	54.6	32.6
1250	88.6	49.7	34.8
1,600	92.6	48.8	40.7
2,000	92.7	44.6	45.0
2,500	90.4	40.8	46.2
3,150	90.0	39.1	48.0
4,000	89.1	37.4	48.2
5,000	88.1	34.3	49.9



Frequency, Hz	Practical Flanking noise (dB)
250	20.8
250	23.9
500	29.2
1,000	33.2
2,000	44.5
4,000	48.8

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 34
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 34

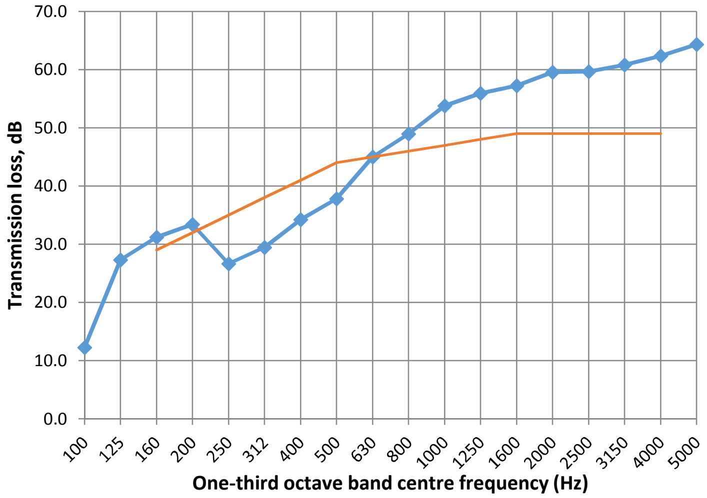
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35
Description of specimen: 10 mm plasterboard backing
25 mm glass fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 10.2 kg/m^2
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m^2
Receiving room – 46.66 m^2
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m^2
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	78.2	61.2	12.3
125	89.2	57.9	27.3
160	92.1	57.8	31.2
200	97.5	60.9	33.4
250	100.0	69.8	26.6
315	98.8	66.1	29.4
400	97.6	60.3	34.2
500	96.9	56.0	37.8
630	95.3	47.0	45.0
800	96.1	43.8	49.0
1,000	96.0	38.7	53.8
1250	93.6	35.8	55.9
1,600	97.6	39.0	57.2
2,000	97.7	36.9	59.5
2,500	95.4	33.6	59.6
3,150	95.0	32.4	60.8
4,000	94.1	29.4	62.3
5,000	93.1	25.8	64.3



Frequency, Hz	Practical Flanking noise (dB)
250	27.9
250	30.7
500	41.3
1,000	53.7
2,000	58.9
4,000	62.7

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 45
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 45

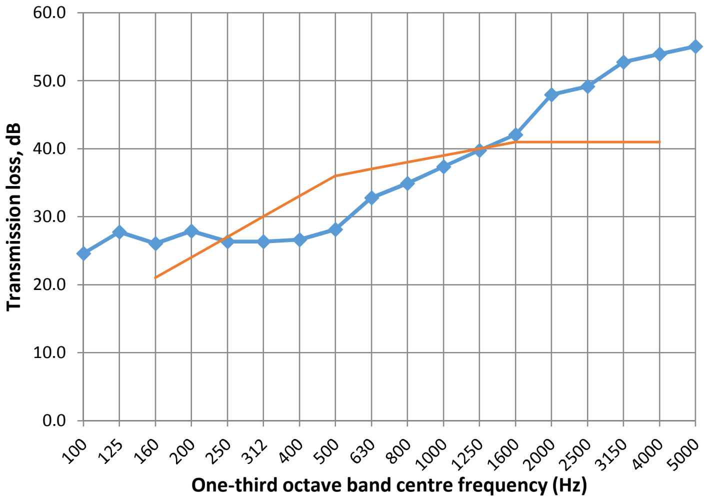
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 4.7 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	73.2	43.9	24.6
125	83.4	51.1	27.7
160	86.6	57.2	26.1
200	89.4	58.3	27.9
250	91.6	61.4	26.3
315	90.2	60.9	26.3
400	90.7	60.9	26.6
500	90.4	59.2	28.1
630	89.0	52.3	32.8
800	89.3	50.4	34.9
1,000	89.6	48.3	37.3
1250	88.4	45.6	39.8
1,600	91.6	46.9	42.1
2,000	91.2	42.2	47.9
2,500	90.2	38.5	49.2
3,150	88.6	34.2	52.7
4,000	87.7	31.6	53.9
5,000	86.1	28.4	55.1



Frequency, Hz	Practical Flanking noise (dB)
250	26.3
250	26.9
500	30.0
1,000	37.8
2,000	47.3
4,000	54.0

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 37
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 37

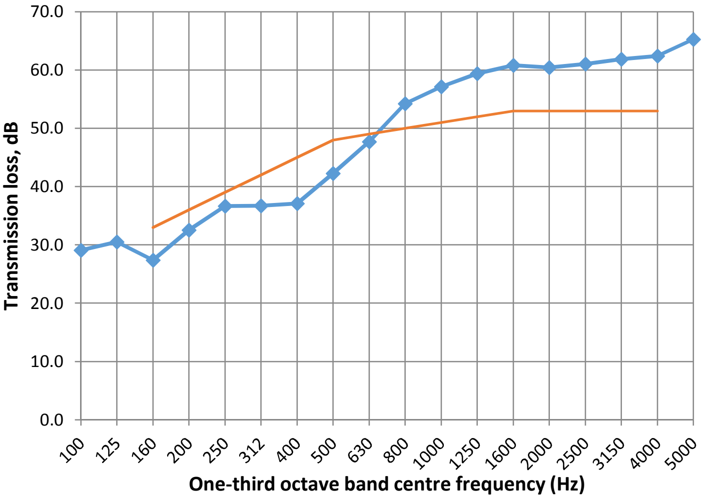
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence
Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 10.8 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 15 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	80.5	46.6	29.1
125	90.2	55.4	30.5
160	93.6	62.9	27.4
200	97.9	61.8	32.6
250	99.9	59.5	36.7
315	99.6	58.8	36.7
400	95.6	54.8	37.1
500	94.5	48.7	42.3
630	93.8	42.3	47.7
800	95.3	37.5	54.2
1,000	95.4	34.8	57.1
1250	95.6	32.9	59.4
1,600	96.9	33.5	60.8
2,000	97.5	34.3	60.4
2,500	97.3	33.9	61.1
3,150	95.7	31.8	61.9
4,000	93.9	29.2	62.4
5,000	93.1	24.9	65.3



Frequency, Hz	Practical Flanking noise (dB)
250	29.2
250	35.7
500	44.3
1,000	57.4
2,000	60.8
4,000	63.5

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 48
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 49

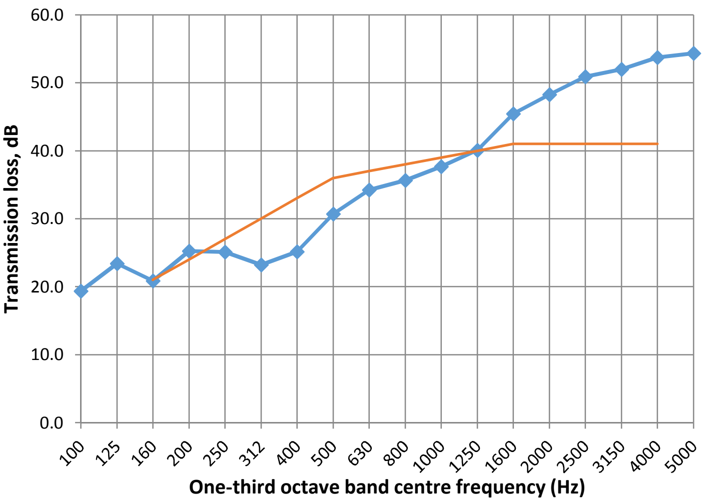
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm porous mineral fibre absorption layer
White painted facing with indentations
Square edged
Size of sample: Full ceiling -
Mass: 3.3 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum space: Additional 15 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	73.2	49.5	19.4
125	84.1	56.1	23.4
160	87.0	63.4	20.9
200	92.3	64.1	25.2
250	94.8	66.9	25.1
315	93.7	68.0	23.2
400	92.5	64.7	25.2
500	91.8	58.2	30.7
630	90.1	52.8	34.2
800	90.7	51.9	35.7
1,000	90.8	49.8	37.7
1250	89.0	44.9	40.1
1,600	93.7	45.8	45.4
2,000	92.8	43.4	48.3
2,500	90.6	36.5	50.9
3,150	90.2	35.9	52.0
4,000	89.4	32.6	53.7
5,000	87.9	29.9	54.3



Frequency, Hz	Practical Flanking noise (dB)
250	21.6
250	24.6
500	31.4
1,000	38.2
2,000	48.7
4,000	53.4

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 37
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 37

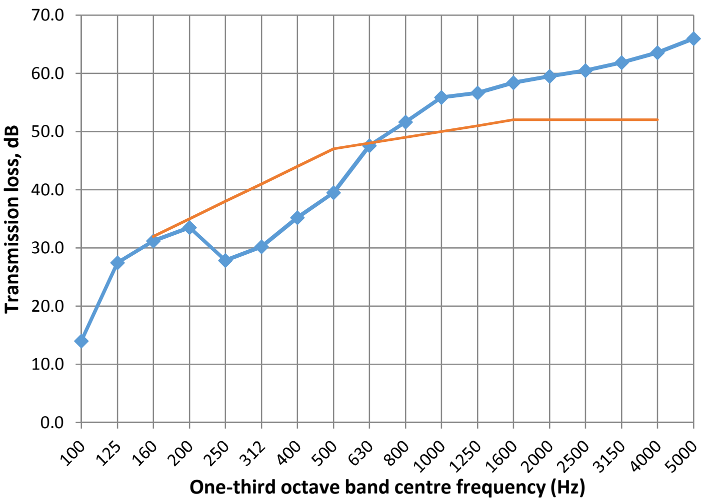
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35
Description of specimen: 10 mm plasterboard backing
25 mm glass fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 10.2 kg/m^2
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m^2
Receiving room – 46.66 m^2
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m^2
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 15 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	83.1	64.3	14.0
125	91.5	60.0	27.5
160	95.7	61.6	31.2
200	99.8	63.1	33.5
250	101.3	70.0	27.8
315	100.4	66.8	30.2
400	98.1	59.7	35.2
500	96.6	54.0	39.5
630	96.5	45.5	47.5
800	97.3	42.3	51.6
1,000	96.7	37.0	55.9
1250	95.2	34.7	56.6
1,600	99.0	37.5	58.4
2,000	98.9	36.8	59.5
2,500	97.2	33.9	60.5
3,150	97.8	33.9	61.9
4,000	95.4	29.4	63.6
5,000	94.4	25.3	65.9



Frequency, Hz	Practical Flanking noise (dB)
250	28.0
250	31.1
500	43.6
1,000	55.2
2,000	59.5
4,000	64.1

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 45
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 45

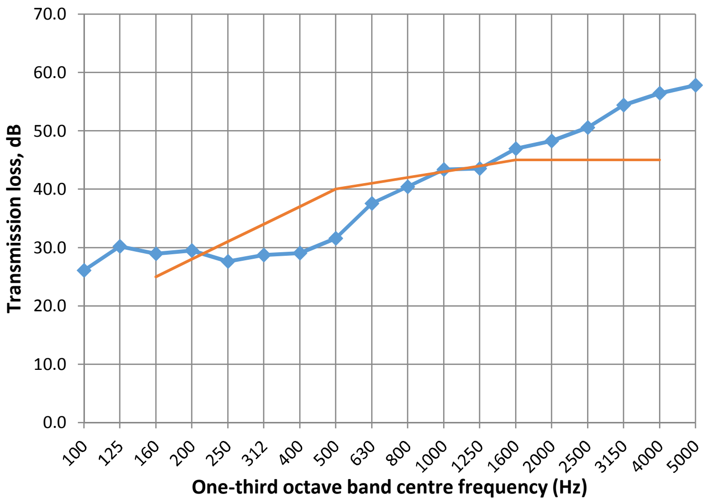
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 4.7 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 15 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	74.2	43.3	26.1
125	82.9	48.3	30.2
160	86.9	54.3	28.9
200	89.4	56.7	29.5
250	91.3	59.9	27.6
315	90.8	59.0	28.7
400	90.5	58.2	29.1
500	90.2	55.8	31.6
630	89.4	48.1	37.6
800	89.4	45.1	40.4
1,000	89.7	42.3	43.4
1250	88.2	40.4	43.5
1,600	91.9	41.3	47.0
2,000	91.1	39.4	48.3
2,500	90.0	36.5	50.6
3,150	88.5	31.7	54.4
4,000	87.7	28.6	56.4
5,000	85.9	25.4	57.8



Frequency, Hz	Practical Flanking noise (dB)
250	28.7
250	28.7
500	34.2
1,000	42.7
2,000	48.9
4,000	56.4

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 41
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 41

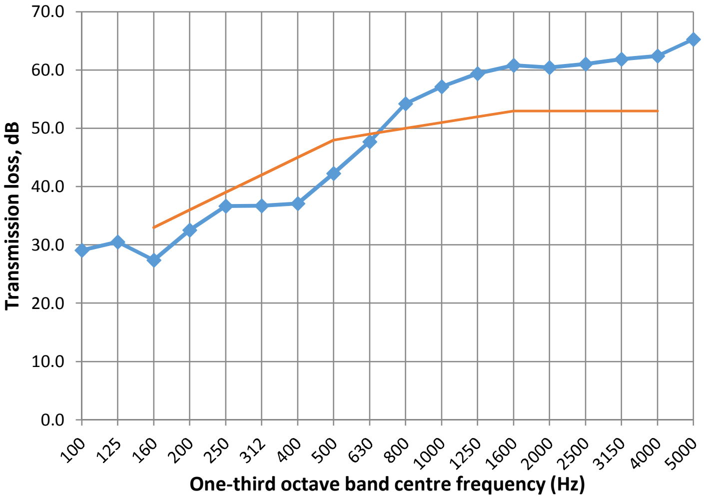
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence
Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 10.8 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 25 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	80.2	45.8	29.8
125	89.3	53.6	31.5
160	93.2	61.0	28.7
200	97.0	59.7	33.8
250	98.8	57.9	37.0
315	98.3	56.9	37.4
400	94.1	53.0	37.4
500	92.7	46.7	42.4
630	92.3	40.0	48.4
800	94.0	35.9	54.7
1,000	95.0	33.9	57.4
1250	93.7	31.1	59.3
1,600	95.3	32.0	60.7
2,000	96.0	31.8	61.6
2,500	96.0	31.2	62.4
3,150	94.6	29.4	62.9
4,000	92.7	26.7	63.8
5,000	91.2	22.4	65.9



Frequency, Hz	Practical Flanking noise (dB)
250	30.1
250	36.3
500	44.9
1,000	57.5
2,000	61.6
4,000	64.4

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 49
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 49

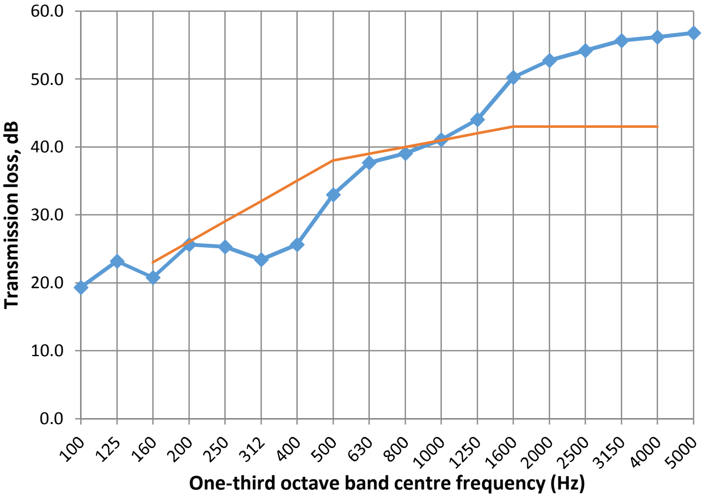
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm porous mineral fibre absorption layer
White painted facing with indentations
Square edged
Size of sample: Full ceiling -
Mass: 3.3 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum space: Additional 25 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	73.2	49.4	19.3
125	84.0	56.3	23.2
160	86.9	63.3	20.8
200	92.1	63.5	25.6
250	94.6	66.3	25.3
315	93.6	67.6	23.4
400	92.3	64.0	25.6
500	91.6	55.6	33.0
630	90.1	49.3	37.7
800	90.6	48.4	39.1
1,000	90.9	46.3	41.1
1250	88.8	40.6	44.1
1,600	93.5	39.4	50.2
2,000	92.3	36.1	52.7
2,500	90.2	32.3	54.2
3,150	89.9	30.9	55.7
4,000	89.3	29.5	56.2
5,000	87.8	27.1	56.8



Frequency, Hz	Practical Flanking noise (dB)
250	21.4
250	24.9
500	34.4
1,000	41.9
2,000	52.7
4,000	56.3

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 39
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 39

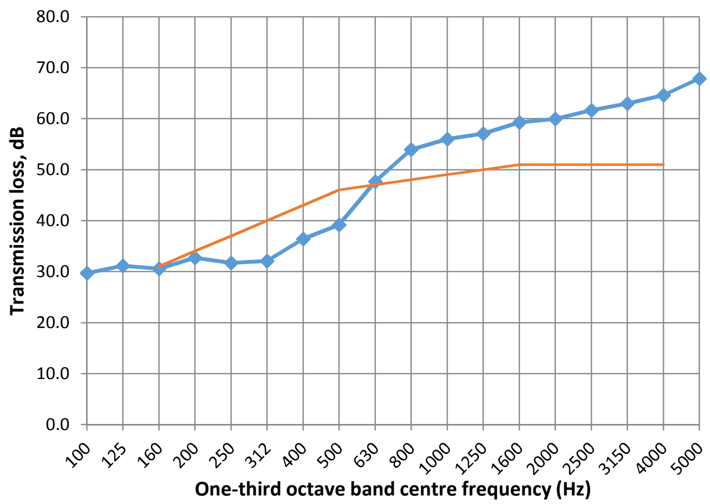
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35
Description of specimen: 10 mm plasterboard backing
25 mm glass fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 10.2 kg/m^2
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m^2
Receiving room – 46.66 m^2
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m^2
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 25 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	82.0	47.5	29.7
125	90.5	55.1	31.1
160	94.7	61.1	30.6
200	98.8	62.8	32.7
250	100.2	64.9	31.7
315	99.3	63.9	32.1
400	97.1	57.5	36.4
500	95.6	53.2	39.2
630	95.4	44.3	47.7
800	96.4	39.1	53.9
1,000	95.8	35.9	56.0
1250	94.2	33.3	57.1
1,600	98.0	35.6	59.3
2,000	97.8	35.2	60.0
2,500	96.0	31.6	61.6
3,150	96.4	31.3	63.0
4,000	94.4	27.1	64.6
5,000	93.3	22.4	67.8



Frequency, Hz	Practical Flanking noise (dB)
250	30.5
250	32.2
500	43.8
1,000	55.9
2,000	60.4
4,000	65.6

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 47
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 47

Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

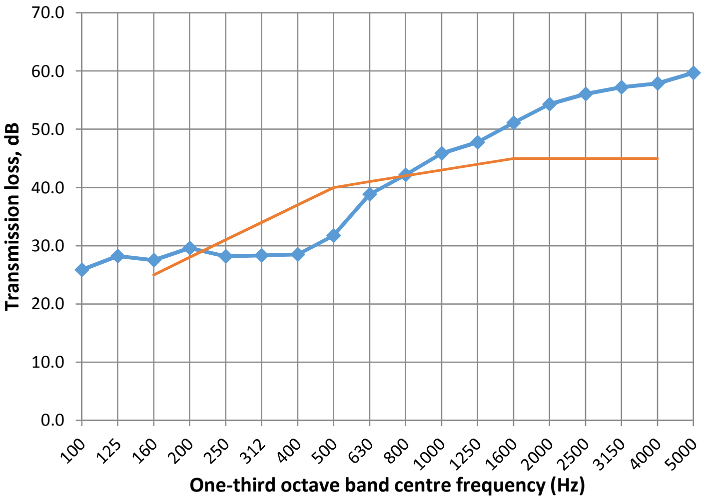
Test specimen: USG Mars

Description of specimen:	19 mm porous mineral fibre absorption layer White glass fibre front tissue facing Square edged
Size of sample:	Full ceiling -
Mass:	4.7 kg/m²
Suspended ceiling grid	USG Donn DXT 38 mm continuous between rooms Designation – C, E, X

Test information: CFN facility at the University of Canterbury

Volume:	Source Room – 46.13 m² Receiving room – 46.66 m²
Partition:	Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen:	7.1 m x 4.5 m – 31.95 m²
Mount:	Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space:	Additional 25 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	74.8	44.1	25.8
125	83.1	50.5	28.2
160	87.2	56.0	27.5
200	89.8	56.7	29.6
250	91.3	59.2	28.2
315	90.7	59.1	28.4
400	89.9	58.2	28.5
500	90.0	55.5	31.8
630	89.6	47.0	38.8
800	89.7	43.5	42.2
1,000	90.0	40.2	45.8
1250	88.5	37.2	47.8
1,600	91.8	37.5	51.1
2,000	91.6	35.2	54.3
2,500	90.5	32.0	56.0
3,150	88.9	30.3	57.2
4,000	87.7	28.0	57.9
5,000	86.1	23.9	59.7



Frequency, Hz	Practical Flanking noise (dB)
250	27.3
250	28.8
500	35.2
1,000	45.8
2,000	54.3
4,000	58.4

Transmission Loss:

Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 41

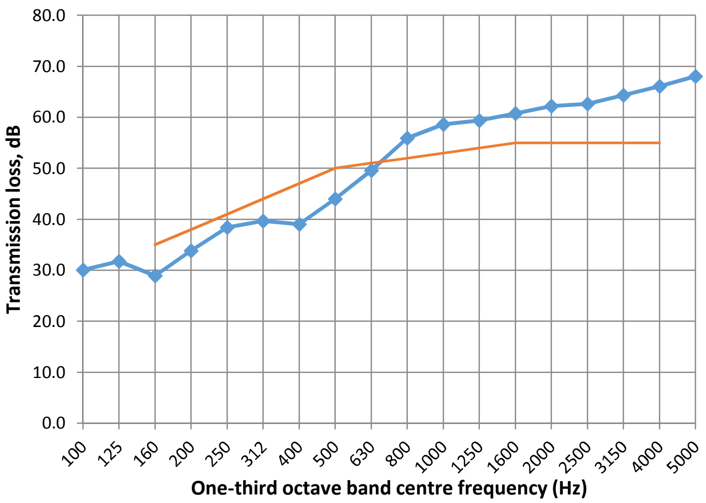
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 41

Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen:	AMF Thermatex Silence
Description of specimen:	13 mm dense mineral fibre backing 30 mm porous mineral fibre absorption layer White glass fibre front tissue facing Square edged
Size of sample:	Full ceiling -
Mass:	10.8 kg/m^2
Suspended ceiling grid	USG Donn DXT 38 mm continuous between rooms Designation – C, E, X
Test information:	CFN facility at the University of Canterbury
Volume:	Source Room – 46.13 m^2 Receiving room – 46.66 m^2
Partition:	Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen:	7.1 m x 4.5 m – 31.95 m^2
Mount:	Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space:	Additional 40 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	83.1	48.3	30.1
125	92.2	56.2	31.7
160	96.2	63.6	28.9
200	99.9	62.5	33.9
250	101.8	59.5	38.4
315	101.1	57.4	39.7
400	97.0	54.3	39.1
500	95.7	48.1	44.0
630	95.1	41.7	49.6
800	97.0	37.6	55.9
1,000	98.0	35.7	58.6
1250	96.5	33.7	59.4
1,600	98.2	34.9	60.7
2,000	98.9	33.9	62.2
2,500	98.4	33.3	62.6
3,150	97.5	30.7	64.3
4,000	95.5	27.2	66.1
5,000	94.2	23.2	68.0



Frequency, Hz	Practical Flanking noise (dB)
250	30.4
250	38.0
500	46.2
1,000	58.2
2,000	61.9
4,000	66.4

Transmission Loss:

Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 50

Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 51

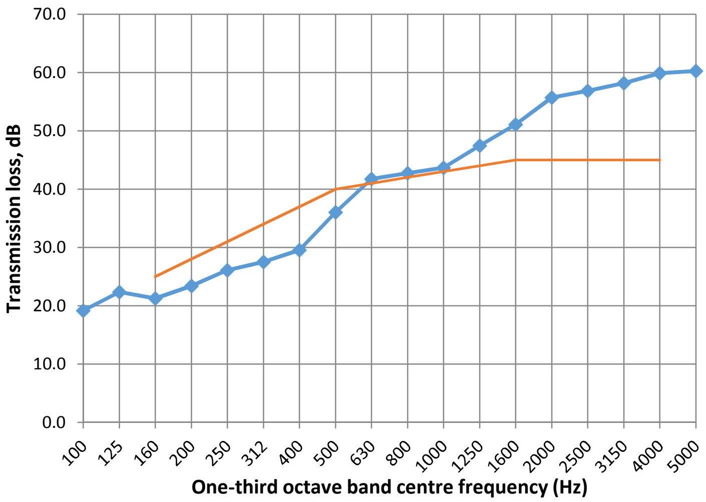
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm porous mineral fibre absorption layer
White painted facing with indentations
Square edged
Size of sample: Full ceiling -
Mass: 3.3 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum space: Additional 25 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	69.6	46.0	19.2
125	73.4	46.6	22.3
160	84.3	60.2	21.3
200	87.1	60.4	23.4
250	92.1	62.9	26.1
315	94.6	64.4	27.5
400	93.8	61.6	29.5
500	92.5	53.5	36.1
630	91.8	47.1	41.8
800	90.3	44.3	42.7
1,000	90.9	43.9	43.7
1250	91.0	39.5	47.5
1,600	89.1	35.7	51.1
2,000	93.9	37.2	55.7
2,500	92.9	32.8	56.9
3,150	90.8	30.3	58.2
4,000	90.4	27.4	59.9
5,000	89.5	25.6	60.3



Frequency, Hz	Practical Flanking noise (dB)
250	21.1
250	26.0
500	38.2
1,000	45.1
2,000	55.2
4,000	59.5

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 41
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 41

Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35

Description of specimen: 10 mm plasterboard backing
25 mm glass fibre absorption layer
White glass fibre front tissue facing
Square edged

Size of sample: Full ceiling -

Mass: 10.2 kg/m^2

Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury

Volume: Source Room – 46.13 m^2
Receiving room – 46.66 m^2

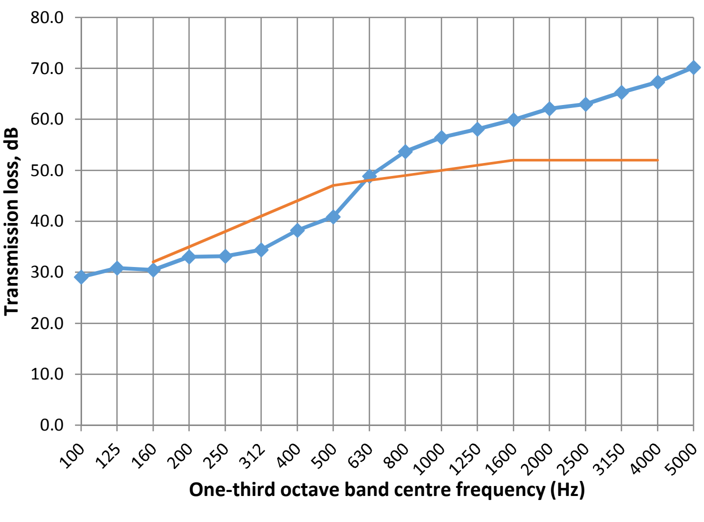
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61

Area of test specimen: 7.1 m x 4.5 m – 31.95 m^2

Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Plenum Space: Additional 40 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	83.1	49.3	29.1
125	91.5	56.6	30.8
160	95.7	62.2	30.4
200	99.8	63.6	33.0
250	101.3	64.5	33.2
315	100.4	62.7	34.4
400	98.2	56.8	38.3
500	96.7	52.8	40.9
630	96.5	44.3	48.8
800	97.4	40.2	53.7
1,000	96.7	36.3	56.4
1250	95.4	33.3	58.1
1,600	98.9	36.0	59.9
2,000	98.8	34.0	62.1
2,500	97.1	31.4	63.0
3,150	97.5	30.0	65.3
4,000	95.7	25.6	67.3
5,000	94.6	21.2	70.2



Frequency, Hz	Practical Flanking noise (dB)
250	30.2
250	33.6
500	45.0
1,000	56.4
2,000	61.8
4,000	68.1

Transmission Loss:

Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 48

Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 48

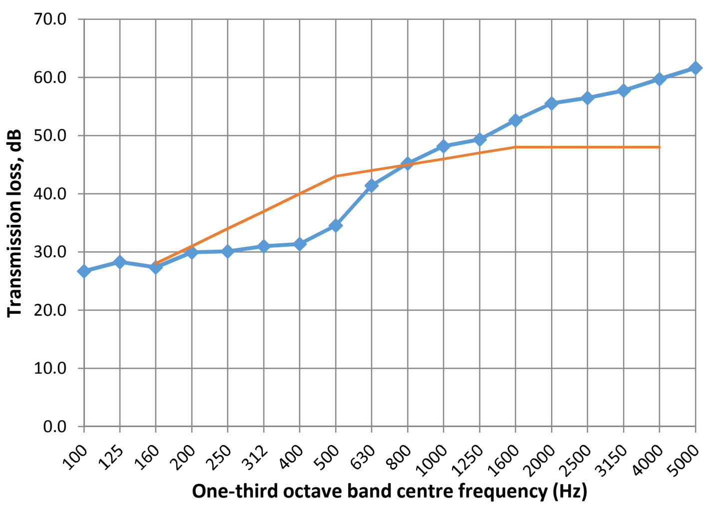
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 4.7 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 40 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	74.7	43.2	26.7
125	83.1	50.4	28.3
160	87.1	56.0	27.4
200	89.8	56.3	29.9
250	91.2	57.0	30.1
315	90.7	56.5	31.0
400	89.9	55.4	31.4
500	89.9	52.6	34.6
630	89.5	44.2	41.4
800	89.8	40.6	45.2
1,000	90.0	37.6	48.2
1250	88.4	34.9	49.3
1,600	92.0	35.7	52.6
2,000	91.4	32.8	55.5
2,500	90.3	31.0	56.5
3,150	88.8	29.2	57.7
4,000	87.5	25.5	59.7
5,000	86.0	21.5	61.6



Frequency, Hz	Practical Flanking noise (dB)
250	27.5
250	30.4
500	37.8
1,000	47.9
2,000	55.2
4,000	60.0

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 44
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 44

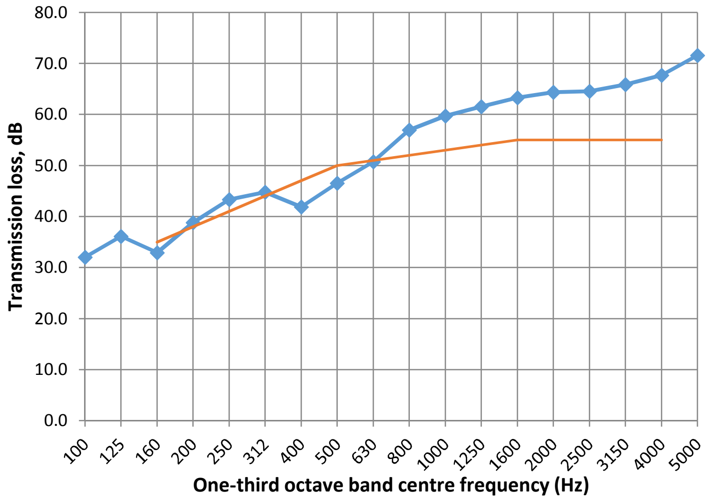
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence
Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 10.8 kg/m^2
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m^2
Receiving room – 46.66 m^2
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m^2
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 100 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	90.0	55.5	32.0
125	99.1	60.4	36.1
160	103.1	67.5	32.9
200	106.8	65.1	38.8
250	108.7	62.7	43.3
315	108.0	60.9	44.8
400	103.9	59.5	41.9
500	102.7	54.0	46.5
630	102.0	48.8	50.7
800	103.9	45.1	56.9
1,000	104.9	43.5	59.7
1250	103.4	41.5	61.5
1,600	105.2	42.4	63.3
2,000	105.8	43.0	64.4
2,500	105.3	42.0	64.5
3,150	104.5	39.6	65.8
4,000	102.4	35.1	67.7
5,000	101.0	28.3	71.6



Frequency, Hz	Practical Flanking noise (dB)
250	34.0
250	43.0
500	47.7
1,000	59.8
2,000	64.1
4,000	69.0

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 50
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 51

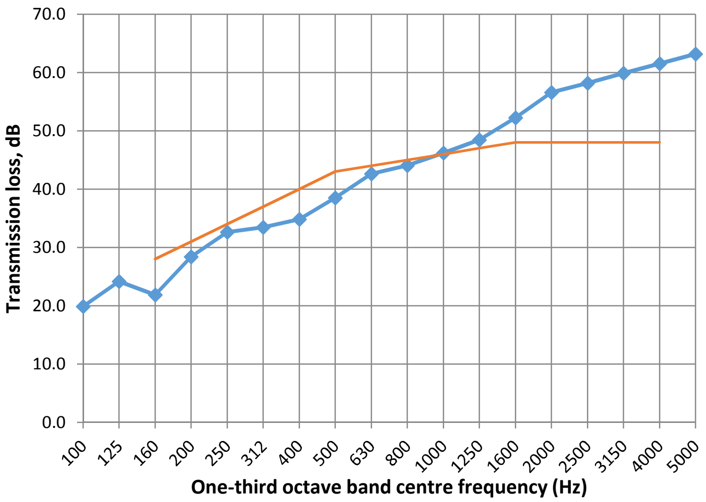
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: Daiken New NDF
Description of specimen: 12 mm porous mineral fibre absorption layer
White painted facing with indentations
Square edged
Size of sample: Full ceiling -
Mass: 3.3 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum space: Additional 100 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	73.3	48.9	19.9
125	83.9	55.1	24.2
160	86.9	62.0	21.9
200	92.0	60.5	28.4
250	94.6	58.7	32.6
315	94.0	58.1	33.5
400	92.6	55.4	34.8
500	91.8	50.5	38.5
630	90.3	44.8	42.6
800	90.9	43.5	44.1
1,000	90.9	41.2	46.2
1250	88.9	36.1	48.5
1,600	93.6	37.5	52.2
2,000	92.6	32.5	56.6
2,500	90.4	28.5	58.2
3,150	90.2	26.8	59.9
4,000	89.6	24.6	61.5
5,000	88.1	21.0	63.2



Frequency, Hz	Practical Flanking noise (dB)
250	22.3
250	32.0
500	39.8
1,000	46.6
2,000	56.3
4,000	61.7

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 44
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 44

Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax Combo 35

Description of specimen: 10 mm plasterboard backing
25 mm glass fibre absorption layer
White glass fibre front tissue facing
Square edged

Size of sample: Full ceiling -

Mass: 10.2 kg/m²

Suspended ceiling grid: USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury

Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²

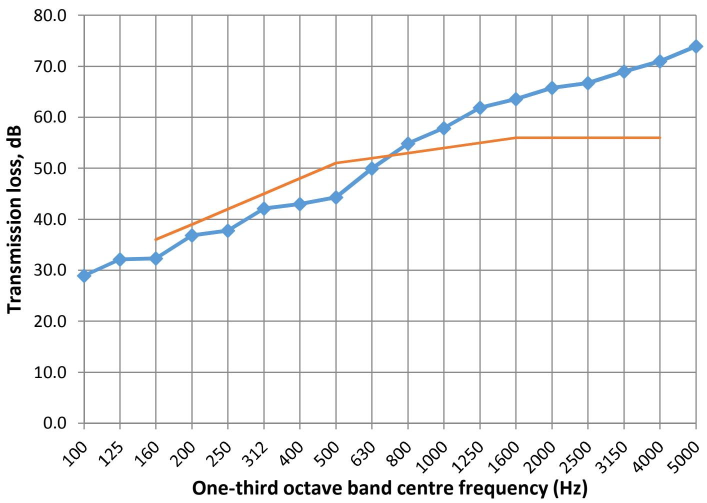
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61

Area of test specimen: 7.1 m x 4.5 m – 31.95 m²

Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Plenum Space: Additional 100 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	86.2	52.4	29.0
125	94.5	58.2	32.1
160	98.8	63.5	32.3
200	102.9	62.8	36.8
250	104.4	62.9	37.8
315	103.4	58.1	42.1
400	101.2	55.1	43.0
500	99.8	52.3	44.3
630	99.6	46.2	50.0
800	100.3	42.0	54.8
1,000	99.7	37.9	57.9
1250	98.3	32.4	61.9
1,600	102.1	35.2	63.6
2,000	101.9	33.5	65.8
2,500	100.3	30.8	66.7
3,150	100.8	29.5	69.0
4,000	98.8	25.2	71.0
5,000	97.5	20.6	73.9



Frequency, Hz	Practical Flanking noise (dB)
250	31.4
250	39.6
500	46.9
1,000	59.1
2,000	65.6
4,000	71.8

Transmission Loss:

Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 52

Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 52

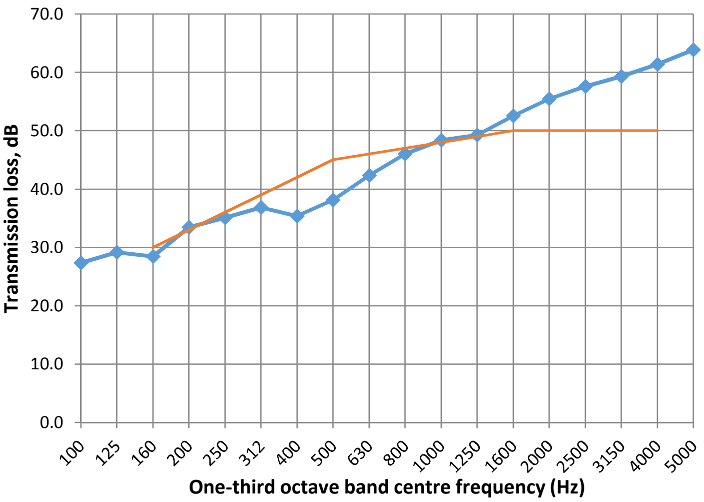
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: USG Mars
Description of specimen: 19 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 4.7 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E, X

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Plenum Space: Additional 100 mm glass fibre absorption lay flat on top of ceiling tiles

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	77.8	45.6	27.3
125	86.0	52.4	29.2
160	90.1	57.9	28.4
200	92.8	55.7	33.4
250	94.3	55.3	35.1
315	93.8	53.8	36.9
400	92.8	54.2	35.4
500	93.0	52.2	38.1
630	92.7	46.6	42.3
800	92.6	42.6	46.0
1,000	93.1	40.7	48.4
1250	91.3	38.4	49.2
1,600	94.7	39.0	52.5
2,000	94.4	37.0	55.5
2,500	93.5	33.5	57.6
3,150	91.7	31.3	59.3
4,000	90.6	27.5	61.4
5,000	89.0	22.7	63.9



Frequency, Hz	Practical Flanking noise (dB)
250	28.4
250	35.3
500	39.6
1,000	48.1
2,000	55.7
4,000	61.9

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 47
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 46

Appendix E – CFN Commissioning Measurements

The results of the commissioning process are given below. Different measurements were conducted throughout the commissioning process and detailed in the order described below. All measurements done through the commissioning process were conducted in direct accordance with the relevant standard.

These results in this appendix are given in the following order:

- Average surface absorption coefficients
  - Before remedial work average surface absorption coefficients for the source room of the CFN facility
  - Before remedial work average surface absorption coefficients for the receiving room of the CFN facility
  - After remedial work average surface absorption coefficients for the source room of the CFN facility
  - After remedial work average surface absorption coefficients for the receiving room of the CFN facility

- TL diffusivity measurements with 25 mm porous ceiling tiles
  - TL of 25 mm porous ceiling tiles with no diffusers
  - TL of 25 mm porous ceiling tiles with 1 diffuser
  - TL of 25 mm porous ceiling tiles with 2 diffusers
  - TL of 25 mm porous ceiling tiles with 3 diffusers
  - TL of 25 mm porous ceiling tiles with 4 diffusers

- Absorption diffusivity measurements with 50 mm porous absorption
  - Sound absorption of a 50 mm porous absorber with no diffusers
  - Sound absorption of a 50 mm porous absorber with 1 diffuser
  - Sound absorption of a 50 mm porous absorber with 2 diffusers
  - Sound absorption of a 50 mm porous absorber with 3 diffusers
  - Sound absorption of a 50 mm porous absorber with 4 diffusers

- TL of the separation wall
  - Before remedial work TL of separating wall
  - After remedial work TL of the separating wall

- Previous CFN facility measurements
    - 25 mm porous ceiling tile
    - AMF Thermatex Silence

Please note that these results shown in this appendix are averages over multiple tests. For simplicity, the results given in these TL results are the average over the multiple tests conducted rather than all tests given.

Average Area Absorption Coefficients According to ASTM E2235-04 Test Method for Determination of Decay Rates for use in Sound Insulation Test Methods

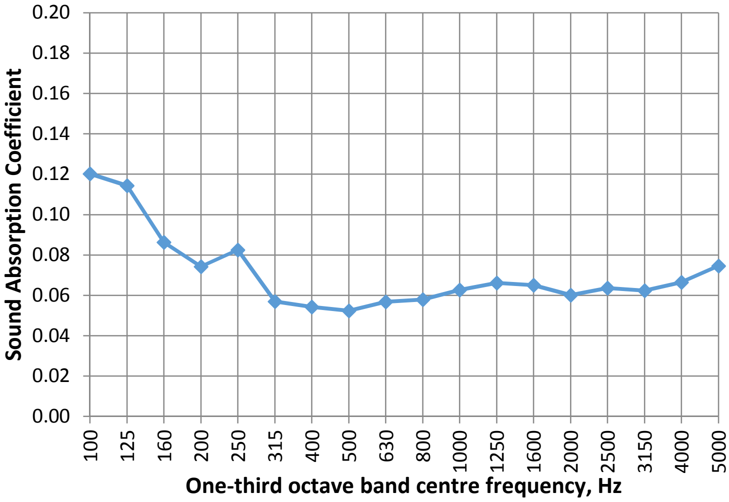
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Source room of the CFN facility
Description of room: Painted plasterboard ceiling tiles
Three walls plywood, one wall unfinished plasterboard
Plywood floor

Test information: Source room of the CFN facility at the University of Canterbury
Volume: 46.13 m^3

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C): 15
Humidity (%): 62
Atmospheric pressure (kPa): 101.04

Frequency, Hz	RT (s)	Decay rate, A_α	Average surface absorption coefficient, A_α
100	0.8	75.9	0.12
125	0.8	72.2	0.11
160	1.1	54.4	0.09
200	1.3	46.9	0.07
250	1.2	52.1	0.08
315	1.7	36.0	0.06
400	1.7	34.3	0.05
500	1.8	33.0	0.05
630	1.7	35.8	0.06
800	1.6	36.6	0.06
1,000	1.5	39.6	0.06
1250	1.4	41.7	0.07
1,600	1.5	41.1	0.07
2,000	1.6	37.9	0.06
2,500	1.5	40.2	0.06
3,150	1.5	39.3	0.06
4,000	1.4	42.0	0.07
5,000	1.3	47.1	0.07



Frequency, Hz	Average surface absorption coefficient (A_α)
125	0.11
250	0.07
500	0.05
1,000	0.06
2,000	0.06
4,000	0.07

Average Area Absorption Coefficients According to ASTM E2235-04 Test Method for Determination of Decay Rates for use in Sound Insulation Test Methods

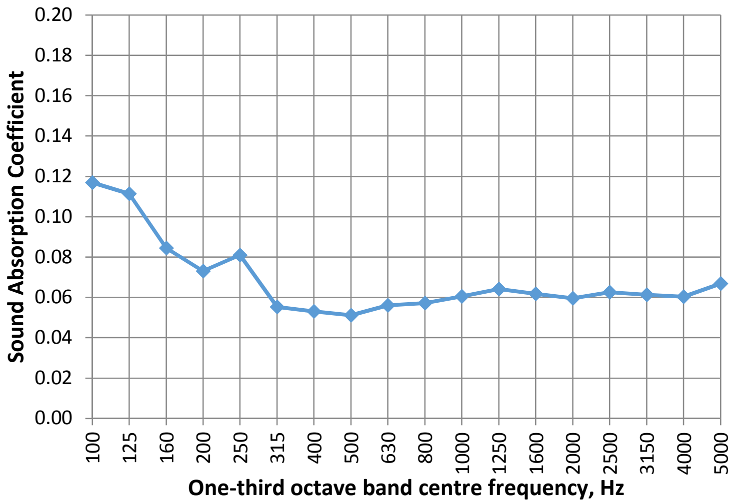
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Receiving room of the CFN facility
Description of room: Painted plasterboard ceiling tiles
Three walls plywood, one wall unfinished plasterboard
Plywood floor

Test information: Source room of the CFN facility at the University of Canterbury
Volume: 46.66 m^3

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C): 15
Humidity (%): 62
Atmospheric pressure (kPa): 101.04

Frequency, Hz	RT (s)	Decay rate, A_α	Average surface absorption coefficient, A_α
100	0.8	73.8	0.12
125	0.9	70.3	0.11
160	1.1	53.3	0.08
200	1.3	46.1	0.07
250	1.2	51.1	0.08
315	1.7	34.9	0.06
400	1.8	33.5	0.05
500	1.9	32.3	0.05
630	1.7	35.4	0.06
800	1.7	36.1	0.06
1,000	1.6	38.2	0.06
1250	1.5	40.5	0.06
1,600	1.5	39.0	0.06
2,000	1.6	37.6	0.06
2,500	1.5	39.5	0.06
3,150	1.6	38.6	0.06
4,000	1.6	38.1	0.06
5,000	1.4	42.2	0.07



Frequency, Hz	Average surface absorption coefficient (A_α)
125	0.10
250	0.07
500	0.05
1,000	0.06
2,000	0.06
4,000	0.06

Average Area Absorption Coefficients According to ASTM E2235-04 Test Method for Determination of Decay Rates for use in Sound Insulation Test Methods

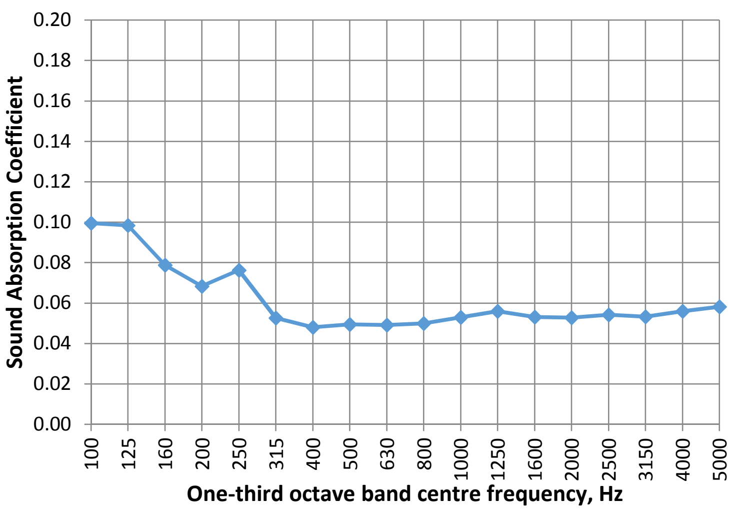
Client: Thesis Research **Date of test:** [Publish Date]

Test specimen: Source room of the CFN facility
Description of room: Painted plasterboard ceiling tiles
Three walls plywood, one wall unfinished plasterboard
Particleboard floor

Test information: Source room of the CFN facility at the University of Canterbury
Volume: 46.13 m³

Environmental conditions: Reverberation Room at the University of Canterbury
Temperature (°C): 15
Humidity (%): 64
Atmospheric pressure (kPa): 100.94

Frequency, Hz	RT (s)	Decay rate, A_α	Average surface absorption coefficient, A_α
100	1.0	62.9	0.10
125	1.0	62.1	0.10
160	1.2	49.7	0.08
200	1.4	43.2	0.07
250	1.2	48.1	0.08
315	1.8	33.3	0.05
400	2.0	30.3	0.05
500	1.9	31.2	0.05
630	1.9	31.0	0.05
800	1.9	31.6	0.05
1,000	1.8	33.4	0.05
1250	1.7	35.4	0.06
1,600	1.8	33.5	0.05
2,000	1.8	33.3	0.05
2,500	1.8	34.2	0.05
3,150	1.8	33.6	0.05
4,000	1.7	35.3	0.06
5,000	1.6	36.7	0.06

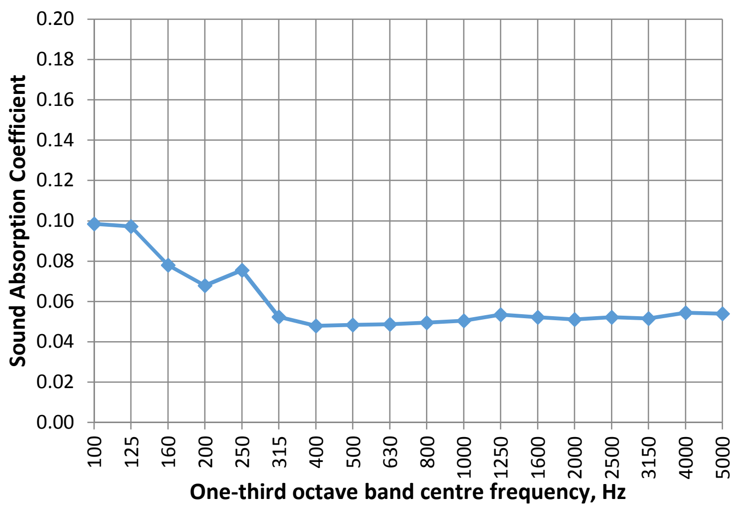


Frequency, Hz	Average surface absorption coefficient (A_α)
125	0.09
250	0.07
500	0.05
1,000	0.05
2,000	0.05
4,000	0.06

Average Area Absorption Coefficients According to ASTM E2235-04
Test Method for Determination of Decay Rates for use in Sound Insulation Test Methods

Client:	Thesis Research	**Date of test:** [Publish Date]
Test specimen:	Receiving room of the CFN facility	
Description of room:	Painted plasterboard ceiling tiles Three walls plywood, one wall unfinished plasterboard Plywood floor	
Test information:	Source room of the CFN facility at the University of Canterbury	
Volume:	46.66 m^3	
Environmental conditions:	Reverberation Room at the University of Canterbury	
Temperature (°C):	15	
Humidity (%):	65	
Atmospheric pressure (kPa):	100.93	

Frequency, Hz	RT (s)	Decay rate, A_α	Average surface absorption coefficient, A_α
100	1.0	62.1	0.10
125	1.0	61.4	0.10
160	1.2	49.2	0.08
200	1.4	42.8	0.07
250	1.3	47.7	0.08
315	1.8	33.0	0.05
400	2.0	30.3	0.05
500	2.0	30.6	0.05
630	2.0	30.7	0.05
800	1.9	31.2	0.05
1,000	1.9	31.8	0.05
1250	1.8	33.8	0.05
1,600	1.8	33.0	0.05
2,000	1.9	32.2	0.05
2,500	1.8	32.9	0.05
3,150	1.8	32.5	0.05
4,000	1.7	34.3	0.05
5,000	1.8	34.0	0.05



Frequency, Hz	Average surface absorption coefficient (A_α)
125	0.09
250	0.07
500	0.05
1,000	0.05
2,000	0.05
4,000	0.05

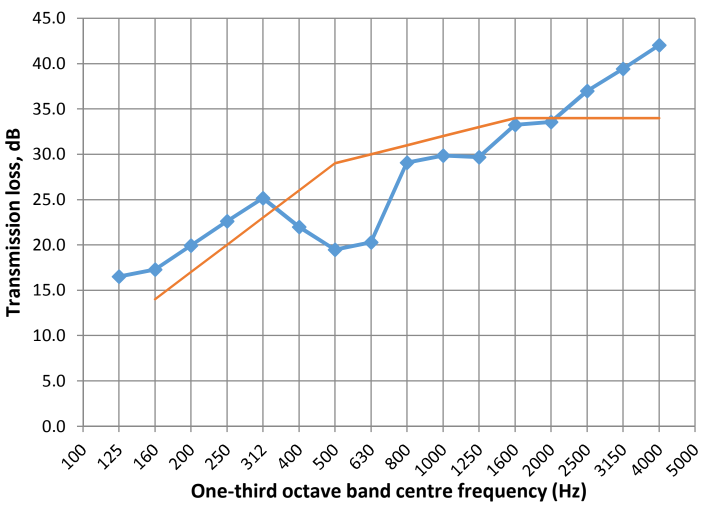
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: CFN facility commissioning **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax 25
Description of specimen: 25 mm glass fibre absorption front
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 1.5 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Diffusers in both rooms: 0

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
125	84.1	63.0	16.5
160	87.0	67.0	17.3
200	92.3	69.4	20.0
250	94.8	69.4	22.6
315	93.7	66.1	25.1
400	92.5	67.9	22.0
500	91.8	69.4	19.5
630	90.1	66.8	20.3
800	90.7	58.5	29.1
1,000	90.8	57.6	29.9
1250	89.0	55.3	29.7
1,600	93.7	58.0	33.2
2,000	92.8	58.1	33.6
2,500	90.6	50.4	37.0
3,150	90.2	48.5	39.4
4,000	89.4	44.2	42.1



Frequency, Hz	Practical Flanking noise (dB)
250	16.9
250	23.1
500	20.7
1,000	29.6
2,000	35.0
4,000	40.9

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 30
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 30

Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: CFN facility commissioning **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax 25

Description of specimen: 25 mm glass fibre absorption front
White glass fibre front tissue facing
Square edged

Size of sample: Full ceiling -

Mass: 1.5 kg/m^2

Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury

Volume: Source Room – 46.13 m^2
Receiving room – 46.66 m^2

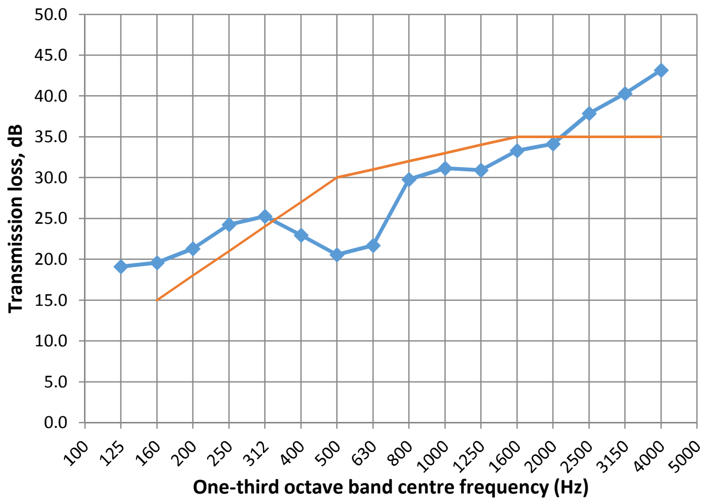
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R$_w$ 61

Area of test specimen: 7.1 m x 4.5 m – 31.95 m^2

Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Diffusers in both rooms: 1

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
125	84.3	60.6	19.1
160	87.1	64.8	19.6
200	92.4	68.2	21.3
250	94.9	67.9	24.2
315	93.9	66.1	25.3
400	92.6	67.0	23.0
500	91.9	68.5	20.6
630	90.2	65.5	21.7
800	90.9	57.9	29.8
1,000	91.0	56.4	31.1
1250	89.1	54.2	30.9
1,600	93.9	58.1	33.3
2,000	92.9	57.7	34.1
2,500	90.7	49.6	37.8
3,150	90.3	47.7	40.3
4,000	89.5	43.3	43.1



Frequency, Hz	Practical Flanking noise (dB)
250	19.4
250	23.9
500	21.9
1,000	30.7
2,000	35.6
4,000	41.9

Transmission Loss:

Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 30

Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 31

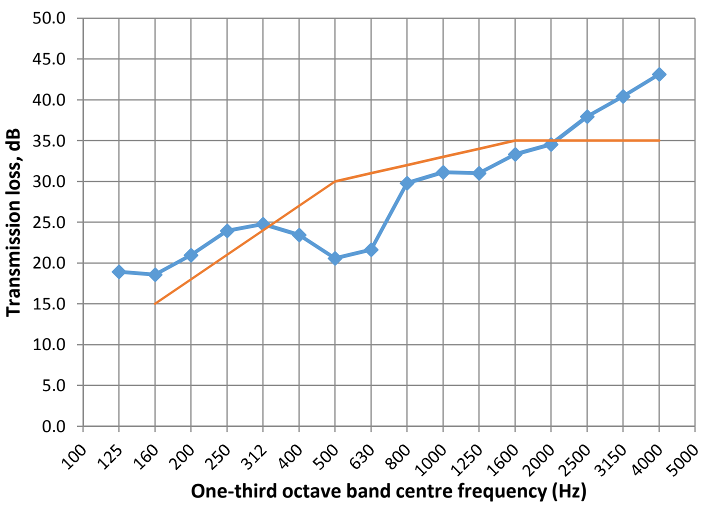
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: CFN facility commissioning **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax 25
Description of specimen: 25 mm glass fibre absorption front
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 1.5 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m³
Receiving room – 46.66 m³
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Diffusers in both rooms: 2

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
125	83.9	60.4	18.9
160	86.8	65.5	18.6
200	92.1	68.2	21.0
250	94.6	67.8	24.0
315	93.5	66.3	24.8
400	92.3	66.2	23.5
500	91.6	68.1	20.6
630	89.9	65.2	21.6
800	90.5	57.5	29.8
1,000	90.6	56.1	31.1
1250	88.8	53.8	31.0
1,600	93.5	57.7	33.3
2,000	92.6	56.9	34.5
2,500	90.4	49.2	37.9
3,150	90.0	47.3	40.4
4,000	89.2	42.9	43.1



Frequency, Hz	Practical Flanking noise (dB)
250	18.8
250	23.5
500	22.1
1,000	30.7
2,000	35.7
4,000	42.0

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 30
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 31

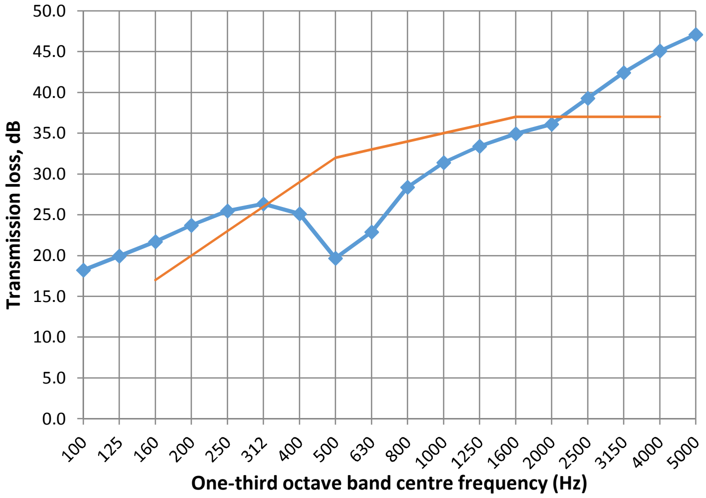
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax 25
Description of specimen: 25 mm glass fibre absorption front
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 1.5 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Diffusers in both rooms: 3

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
125	84.1	59.8	19.6
160	86.9	63.2	21.1
200	92.2	67.5	21.8
250	94.7	67.4	24.5
315	93.7	65.5	25.7
400	92.4	65.3	24.5
500	91.7	68.1	20.8
630	90.0	64.8	22.2
800	90.7	57.0	30.5
1,000	90.8	55.9	31.4
1250	88.9	53.6	31.3
1,600	93.7	57.4	33.8
2,000	92.7	56.6	34.9
2,500	90.5	48.7	38.5
3,150	90.1	46.7	41.1
4,000	89.3	42.8	43.4



Frequency, Hz	Practical Flanking noise (dB)
250	20.4
250	24.3
500	22.8
1,000	31.1
2,000	36.3
4,000	42.4

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 31
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 31

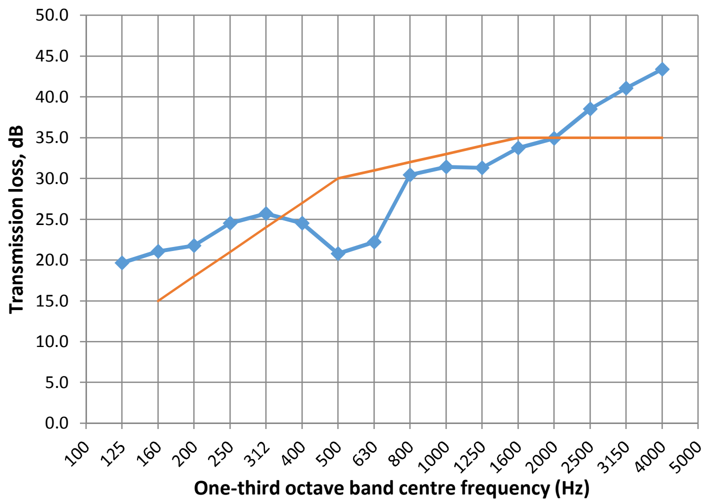
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: CFN facility commissioning **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax 25
Description of specimen: 25 mm glass fibre absorption front
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 1.5 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Diffusers in both rooms: 4

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
125	84.1	59.9	19.6
160	87.0	63.3	21.0
200	92.3	67.6	21.8
250	94.8	67.5	24.5
315	93.7	65.6	25.7
400	92.5	65.4	24.5
500	91.8	68.1	20.8
630	90.1	64.9	22.2
800	90.7	57.1	30.4
1,000	90.8	56.0	31.4
1250	89.0	53.7	31.3
1,600	93.7	57.5	33.7
2,000	92.8	56.8	34.9
2,500	90.6	48.8	38.5
3,150	90.2	46.8	41.1
4,000	89.4	42.9	43.4



Frequency, Hz	Practical Flanking noise (dB)
250	20.4
250	24.3
500	22.8
1,000	31.1
2,000	36.2
4,000	42.4

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 31
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 31

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

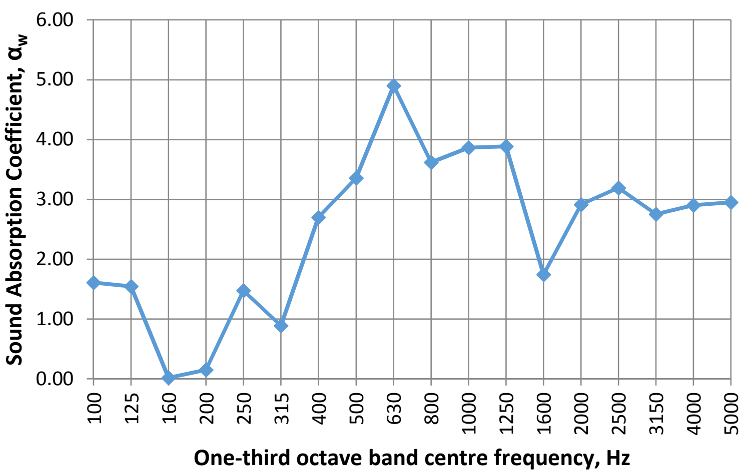
Client: Commissioning of CFN facility **Date of test:** [Publish Date]

Test specimen: 50 mm polyester absorption material
Description of specimen: 50 mm white polyester fibre acoustic insulation
Size of sample: 2000 mm x 1500 mm

Test information: Source room of the CFN facility for diffusion
Volume: ~46 m^3
Area of test specimen: 2.0 m x 1.5 m – 3.0 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame
Diffusion panels: 0

Environmental conditions: Source room of the CFN facility for diffusion
Temperature (^{o}C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	0.61	0.57	1.61
125	0.65	0.60	1.54
160	0.84	0.84	0.01
200	1.04	1.02	0.15
250	1.08	0.95	1.48
315	1.55	1.39	0.89
400	1.80	1.29	2.70
500	1.69	1.16	3.36
630	2.07	1.12	4.90
800	1.67	1.12	3.62
1,000	1.53	1.03	3.87
1250	1.31	0.93	3.88
1,600	1.21	1.04	1.74
2,000	1.22	0.94	2.91
2,500	1.24	0.93	3.19
3,150	1.24	0.97	2.75
4,000	1.21	0.94	2.90
5,000	1.12	0.88	2.95



Frequency, Hz	Practical sound absorption coefficient (α_p)
125	1.00
250	0.85
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 1.00
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 1.00

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

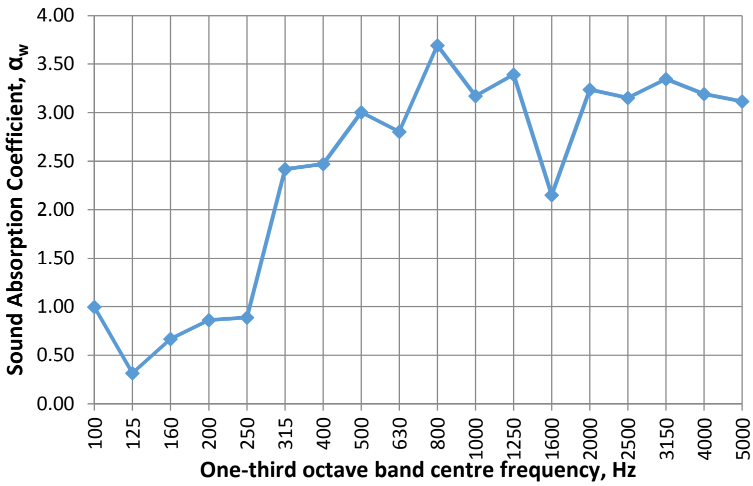
Client: Commissioning of CFN facility **Date of test:** [Publish Date]

Test specimen: 50 mm polyester absorption material
Description of specimen: 50 mm white polyester fibre acoustic insulation
Size of sample: 2000 mm x 1500 mm

Test information: Source room of the CFN facility for diffusion
Volume: ~46 m^3
Area of test specimen: 2.0 m x 1.5 m – 3.0 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame
Diffusion panels: 1

Environmental conditions: Source room of the CFN facility for diffusion
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	0.59	0.56	1.00
125	0.58	0.58	0.32
160	0.80	0.77	0.67
200	1.03	0.96	0.86
250	0.94	0.88	0.89
315	1.38	1.08	2.42
400	1.48	1.14	2.47
500	1.63	1.19	3.00
630	1.57	1.16	2.80
800	1.60	1.08	3.69
1,000	1.45	1.06	3.17
1250	1.26	0.94	3.39
1,600	1.19	0.98	2.15
2,000	1.19	0.90	3.24
2,500	1.19	0.91	3.15
3,150	1.24	0.93	3.35
4,000	1.18	0.90	3.19
5,000	1.09	0.85	3.12



Frequency, Hz	Practical sound absorption coefficient (α_p)
125	0.65
250	1.00
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 1.00
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 1.00

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

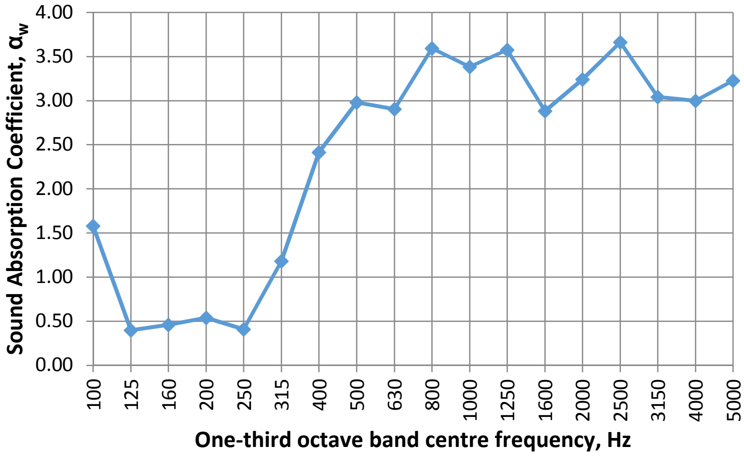
Client: Commissioning of CFN facility **Date of test:** [Publish Date]

Test specimen: 50 mm polyester absorption material
Description of specimen: 50 mm white polyester fibre acoustic insulation
Size of sample: 2000 mm x 1500 mm

Test information: Source room of the CFN facility for diffusion
Volume: ~46 m^3
Area of test specimen: 2.0 m x 1.5 m – 3.0 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame
Diffusion panels: 2

Environmental conditions: Source room of the CFN facility for diffusion
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	0.55	0.52	1.58
125	0.57	0.56	0.40
160	0.77	0.75	0.46
200	0.90	0.87	0.54
250	0.91	0.88	0.41
315	1.22	1.09	1.18
400	1.43	1.11	2.42
500	1.52	1.11	2.98
630	1.59	1.15	2.91
800	1.56	1.07	3.59
1,000	1.40	1.01	3.38
1250	1.28	0.93	3.58
1,600	1.21	0.94	2.88
2,000	1.18	0.90	3.24
2,500	1.21	0.89	3.66
3,150	1.19	0.92	3.04
4,000	1.14	0.89	3.00
5,000	1.08	0.84	3.23



Frequency, Hz	Practical sound absorption coefficient (α_p)
125	0.80
250	0.70
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 1.00
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 1.00

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

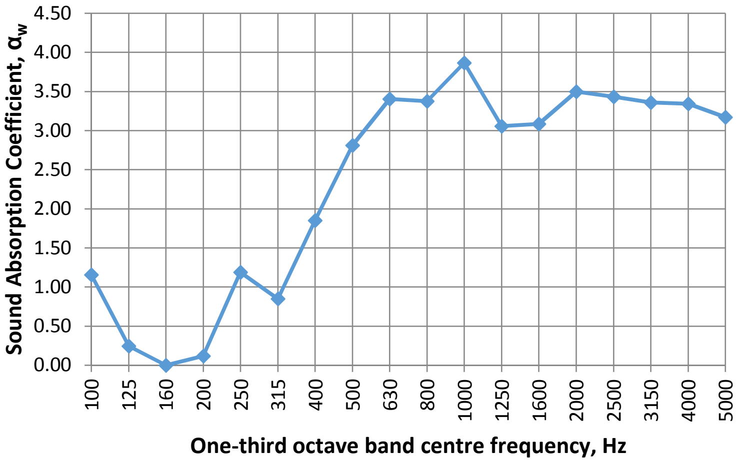
Client: Commissioning of CFN facility **Date of test:** [Publish Date]

Test specimen: 50 mm polyester absorption material
Description of specimen: 50 mm white polyester fibre acoustic insulation
Size of sample: 2000 mm x 1500 mm

Test information: Source room of the CFN facility for diffusion
Volume: ~46 m^3
Area of test specimen: 2.0 m x 1.5 m – 3.0 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame
Diffusion panels: 3

Environmental conditions: Source room of the CFN facility for diffusion
Temperature (^oC):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	0.56	0.53	1.16
125	0.56	0.55	0.24
160	0.73	0.74	0.00
200	0.81	0.80	0.12
250	0.96	0.88	1.19
315	1.13	1.04	0.85
400	1.36	1.13	1.85
500	1.48	1.10	2.81
630	1.55	1.08	3.40
800	1.55	1.09	3.37
1,000	1.35	0.94	3.87
1250	1.20	0.93	3.06
1,600	1.17	0.94	3.09
2,000	1.18	0.86	3.50
2,500	1.19	0.89	3.43
3,150	1.18	0.88	3.36
4,000	1.13	0.86	3.35
5,000	1.07	0.82	3.17



Frequency, Hz	Practical sound absorption coefficient (α_p)
125	0.45
250	0.70
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 1.00
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 1.00

Sound Absorption Coefficients According to ISO 354:2003
Acoustics – Measurement of sound absorption in a reverberation room

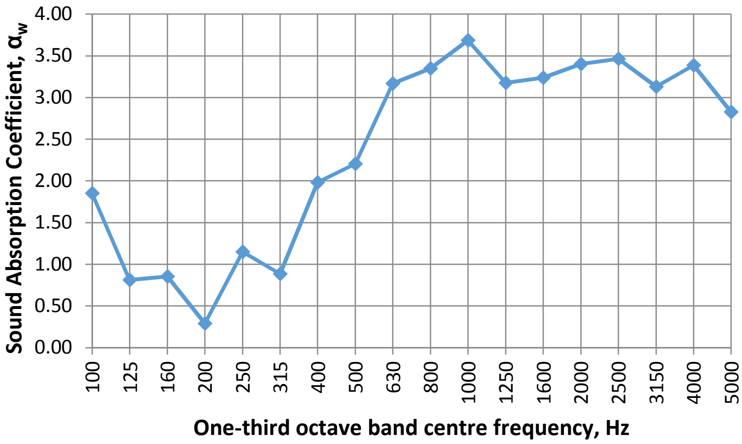
Client: Commissioning of CFN facility **Date of test:** [Publish Date]

Test specimen: 50 mm polyester absorption material
Description of specimen: 50 mm white polyester fibre acoustic insulation
Size of sample: 2000 mm x 1500 mm

Test information: Source room of the CFN facility for diffusion
Volume: ~46 m^3
Area of test specimen: 2.0 m x 1.5 m – 3.0 m^2
Mount: Mount Type A according to ISO 354:2003, arranged with enclosing frame
Diffusion panels: 4

Environmental conditions: Source room of the CFN facility for diffusion
Temperature (°C):
Humidity (%):
Atmospheric pressure (kPa):

Frequency, Hz	T_1 Empty room (s)	T_2 Full room (s)	α_s
100	0.58	0.53	1.85
125	0.59	0.57	0.81
160	0.81	0.77	0.86
200	0.85	0.83	0.29
250	0.98	0.89	1.15
315	1.22	1.13	0.88
400	1.35	1.11	1.98
500	1.39	1.11	2.20
630	1.50	1.08	3.17
800	1.45	1.04	3.35
1,000	1.45	1.01	3.69
1250	1.22	0.92	3.17
1,600	1.14	0.88	3.24
2,000	1.15	0.87	3.40
2,500	1.15	0.87	3.46
3,150	1.16	0.90	3.13
4,000	1.11	0.85	3.39
5,000	1.04	0.84	2.83



Frequency, Hz	Practical sound absorption coefficient (α_p)
125	1.00
250	0.75
500	1.00
1,000	1.00
2,000	1.00
4,000	1.00

Absorption Coefficient:
Weighted sound absorption coefficient according to ISO 11654:1997: 1.00
Sound absorption class: A
Sound absorption average according to ASTM C423-09a: 1.00

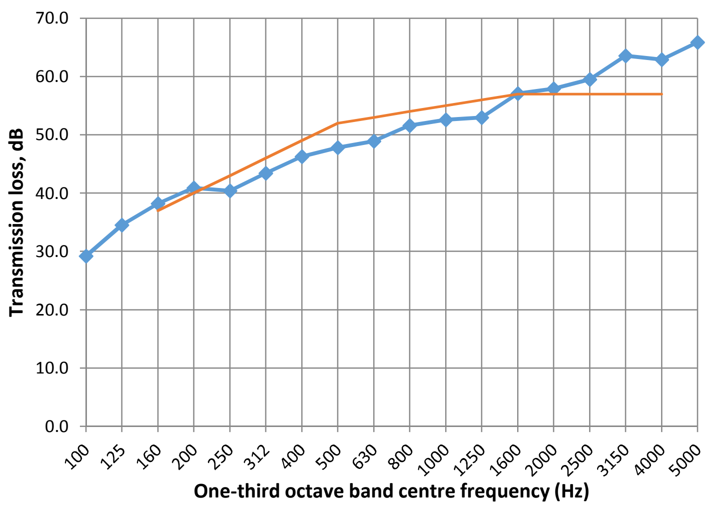
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: CFN facility commissioning **Date of test:** [Publish Date]

Test specimen: Separating wall
Description of specimen: 13 Standard GIB plasterboard / 18 mm MDF / 4kg/m² mass loaded barrier / 2 90 mm stud separated by 10 mm with 75 mm fibrous absorption / 18 mm plywood / GIB ST-001 clip / 2 layers 13 mm GIB Noiseline
Size of sample: All flanking paths
Mass: -
Suspended ceiling grid: 3 layers of 13 mm plasterboard ceiling tiles / 2 layers of 4 kg/m² mass loaded barrier directly over / 4 kg/m² and 6 kg/m² mass loaded barrier suspended from roof / 600 mm wide baffle blocks either side on hung mass loaded barrier.

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: All wall noise paths
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
Diffusers in both rooms: 4

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
125	79.0	47.2	29.2
160	89.2	52.3	34.5
200	93.9	54.6	38.2
250	99.3	57.9	40.9
315	100.4	59.1	40.4
400	101.8	59.1	43.4
500	99.5	54.1	46.3
630	99.8	53.0	47.8
800	99.6	51.4	48.9
1,000	101.9	50.9	51.6
1250	101.8	49.5	52.6
1,600	99.8	46.8	53.0
2,000	103.1	46.1	57.1
2,500	103.4	45.9	57.9
3,150	102.0	42.7	59.5
4,000	101.5	38.2	63.6



Frequency, Hz	Practical Flanking noise (dB)
250	35.3
250	41.8
500	47.8
1,000	52.4
2,000	58.3
4,000	64.3

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 53
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 53

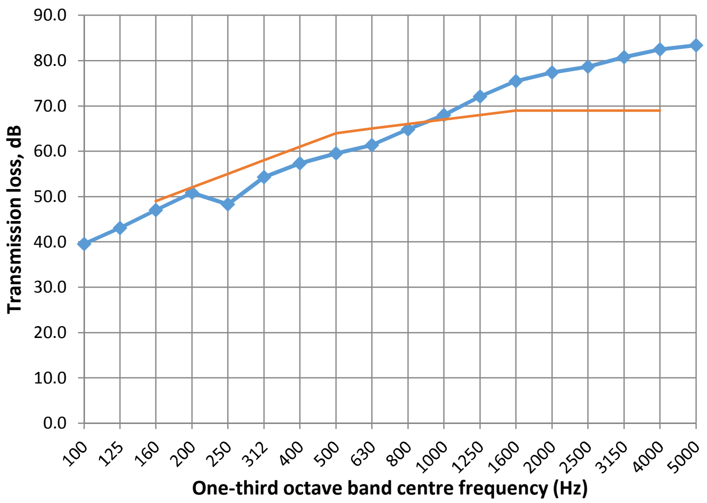
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: CFN facility commissioning **Date of test:** [Publish Date]

Test specimen: Separating wall
- Description of specimen: 13 Standard GIB plasterboard / 18 mm MDF / 4kg/m² mass loaded barrier / 2 90 mm stud separated by 10 mm with 75 mm fibrous absorption / 18 mm plywood / GIB ST-001 clip / 2 layers 13 mm GIB Noiseline
- Size of sample: All flanking paths
- Mass: -
- Suspended ceiling grid: 3 layers of 13 mm plasterboard ceiling tiles / 2 layers of 4 kg/m² mass loaded barrier directly over / 4 kg/m² and 6 kg/m² mass loaded barrier suspended from roof / 600 mm wide baffle blocks either side on hung mass loaded barrier.

Test information: CFN facility at the University of Canterbury
- Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
- Partition: Calculating the transmission loss for in test
- Area of test specimen: All wall noise paths
- Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms
- Diffusers in both rooms: 3

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
125	83.5	41.3	39.5
160	93.7	48.2	43.1
200	98.4	50.3	47.0
250	103.8	52.4	50.8
315	104.9	55.7	48.3
400	106.3	52.7	54.3
500	104.0	47.6	57.3
630	104.4	45.8	59.5
800	104.1	43.4	61.4
1,000	106.4	42.1	64.8
1250	106.3	38.6	68.0
1,600	104.3	32.2	72.1
2,000	107.6	32.3	75.5
2,500	108.0	31.0	77.4
3,150	106.6	28.1	78.6
4,000	106.0	25.6	80.7



Frequency, Hz	Practical Flanking noise (dB)
250	44.2
250	51.8
500	59.7
1,000	69.3
2,000	77.4
4,000	82.3

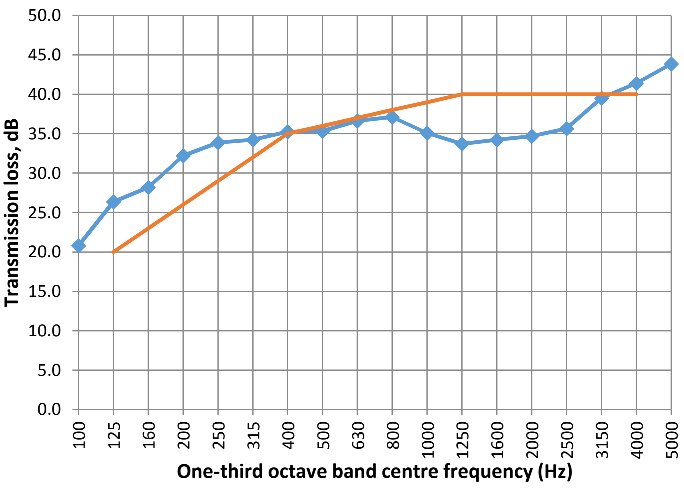
Transmission Loss:
- Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 65
- Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 65

Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: External wall 1 of the CFN facility
Description of specimen: 18 mm plywood
90 mm timber frame with 90 mm fibrous insulation
18 mm plywood
Size of sample: All wall ~ 12.5 m²
Mass: Unknown

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	2.93	0.34	14.0
125	7.17	0.24	20.8
160	6.77	0.71	26.4
200	6.17	0.44	28.2
250	6.53	0.42	32.2
315	6.07	0.37	33.9
400	5.87	0.50	34.2
500	6.00	0.95	35.3
630	6.50	0.9	35.3
800	7.44	0.91	36.6
1,000	7.27	0.85	37.1
1250	6.77	0.92	35.1
1,600	6.83	0.65	33.7
2,000	6.74	0.54	34.2
2,500	5.77	0.87	34.7
3,150	5.21	0.54	35.7
4,000	5.51	0.95	39.5
5,000	5.64	0.94	41.4



Frequency, Hz	Practical Transmission Loss (dB)
125	26.1
250	33.5
500	35.5
1,000	35.5
2,000	34.9
4,000	41.9

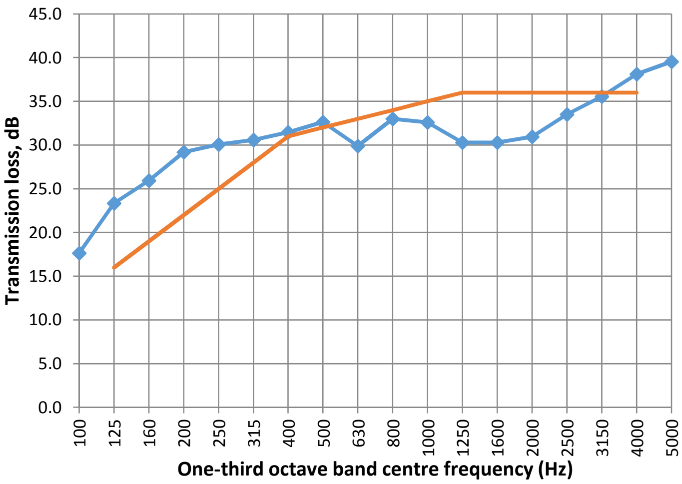
Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 36
Spectrum adaption, C, C_{tr}: -1, -2
Sound transmission class (STC) in accordance with ASTM E413-10: 36

Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: External wall 2 of the CFN facility
Description of specimen: 18 mm plywood
90 mm timber frame with 90 mm fibrous insulation
18 mm plywood
Size of sample: All wall ~ 16.7 m²
Mass: Unknown

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	4.27	0.37	17.6
125	5.67	0.87	23.4
160	5.70	0.63	25.9
200	5.43	0.17	29.2
250	5.90	0.47	30.1
315	5.74	0.27	30.6
400	5.93	0.20	31.5
500	6.23	0.30	32.6
630	6.40	0.74	29.9
800	7.00	0.33	33.0
1,000	7.07	0.55	32.6
1250	6.60	0.61	30.3
1,600	6.27	0.30	30.3
2,000	6.17	0.27	31.0
2,500	5.77	0.30	33.5
3,150	5.90	0.25	35.6
4,000	6.17	0.31	38.1
5,000	7.14	0.45	39.5



Frequency, Hz	Practical Transmission Loss (dB)
125	23.5
250	30.0
500	31.5
1,000	32.1
2,000	31.8
4,000	38.0

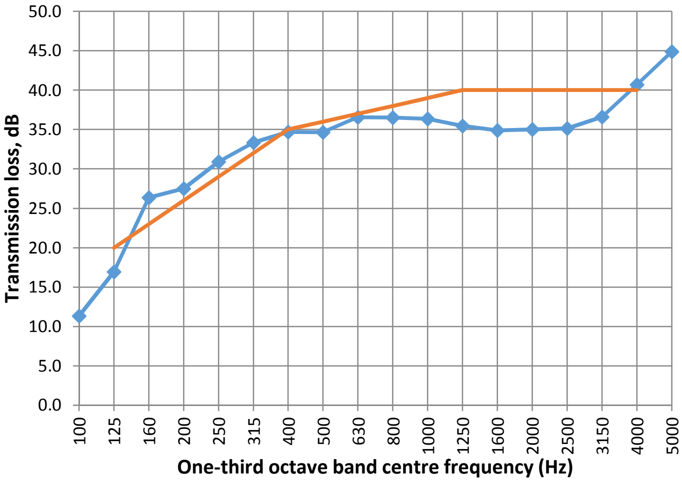
Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 32
Spectrum adaption, C, C_{tr}: -1, -2
Sound transmission class (STC) in accordance with ASTM E413-10: 32

Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: External wall 3 of the CFN facility
Description of specimen: 18 mm plywood
90 mm timber frame with 90 mm fibrous insulation
18 mm plywood
Size of sample: All wall ~ 12.5 m²
Mass: Unknown

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	2.93	0.34	11.3
125	7.17	0.24	16.9
160	6.77	0.71	26.4
200	6.17	0.44	27.5
250	6.53	0.42	30.9
315	6.07	0.37	33.4
400	5.87	0.50	34.7
500	6.00	0.95	34.7
630	6.50	0.9	36.6
800	7.44	0.91	36.5
1,000	7.27	0.85	36.4
1250	6.77	0.92	35.5
1,600	6.83	0.65	34.9
2,000	6.74	0.54	35.0
2,500	5.77	0.87	35.1
3,150	5.21	0.54	36.6
4,000	5.51	0.95	40.7
5,000	5.64	0.94	44.9



Frequency, Hz	Practical Transmission Loss (dB)
125	22.2
250	31.2
500	35.4
1,000	36.1
2,000	35.0
4,000	42.0

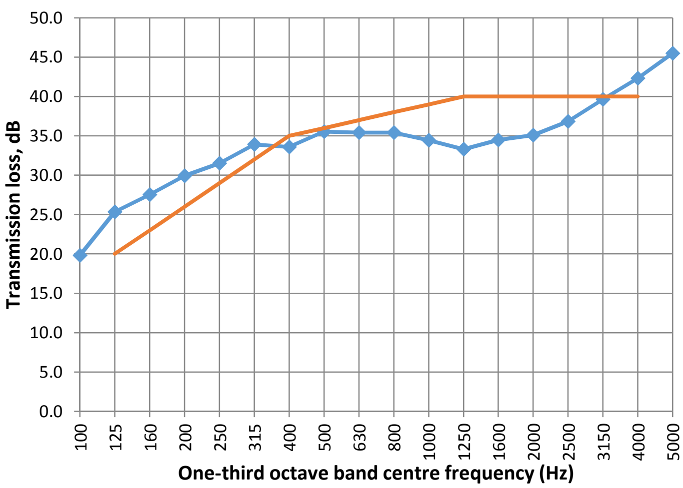
Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 36
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 36

Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: External wall 4 of the CFN facility
Description of specimen: 18 mm plywood
90 mm timber frame with 90 mm fibrous insulation
18 mm plywood
Size of sample: All wall ~ 12.5 m²
Mass: Unknown

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	3.97	0.33	19.8
125	5.75	0.40	25.3
160	5.83	0.33	27.5
200	5.97	0.50	29.9
250	6.52	0.50	31.5
315	6.31	0.40	33.9
400	6.07	0.20	33.6
500	6.80	0.14	35.6
630	7.21	0.51	35.4
800	7.93	0.27	35.4
1,000	8.25	0.65	34.4
1250	7.37	0.48	33.3
1,600	6.77	0.17	34.5
2,000	6.70	0.40	35.1
2,500	6.10	0.37	36.9
3,150	5.53	0.37	39.6
4,000	6.00	0.47	42.3
5,000	6.73	0.22	45.5



Frequency, Hz	Practical Transmission Loss (dB)
125	25.2
250	32.1
500	34.9
1,000	34.5
2,000	35.6
4,000	43.1

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 36
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 36

Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

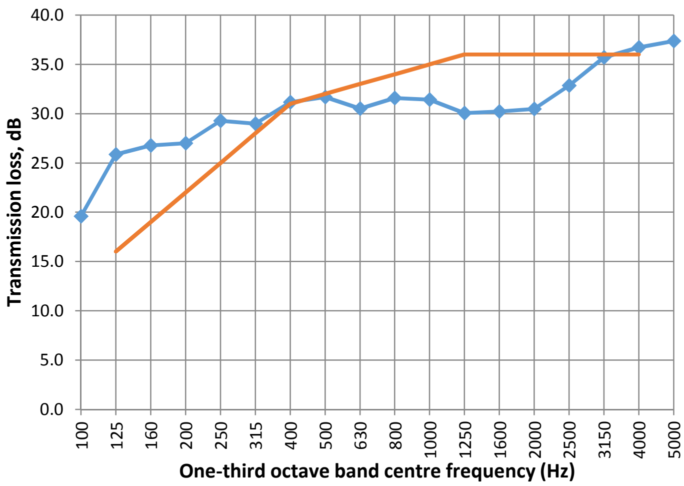
Test specimen: External wall 5 of the CFN facility

Description of specimen: 18 mm plywood
90 mm timber frame with 90 mm fibrous insulation
18 mm plywood

Size of sample: All wall ~ 16.7 m²

Mass: Unknown

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	5.14	0.87	19.6
125	7.04	0.30	25.9
160	6.30	0.14	26.8
200	6.00	0.66	27.0
250	6.57	0.23	29.3
315	5.97	0.27	29.0
400	5.55	0.13	31.1
500	5.36	0.21	31.7
630	6.67	0.35	30.5
800	6.77	0.56	31.6
1,000	7.14	0.75	31.4
1250	6.80	0.35	30.1
1,600	6.37	0.89	30.2
2,000	5.90	0.21	30.5
2,500	5.37	0.36	32.9
3,150	5.50	0.23	35.7
4,000	5.57	0.28	36.7
5,000	5.45	0.46	37.4



Frequency, Hz	Practical Transmission Loss (dB)
125	25.0
250	28.5
500	31.1
1,000	31.1
2,000	31.4
4,000	36.7

Transmission Loss:

Weighted sound reduction index in accordance with ISO 717-1:2000: 32

Spectrum adaption, C, C_{tr}: -1, -2

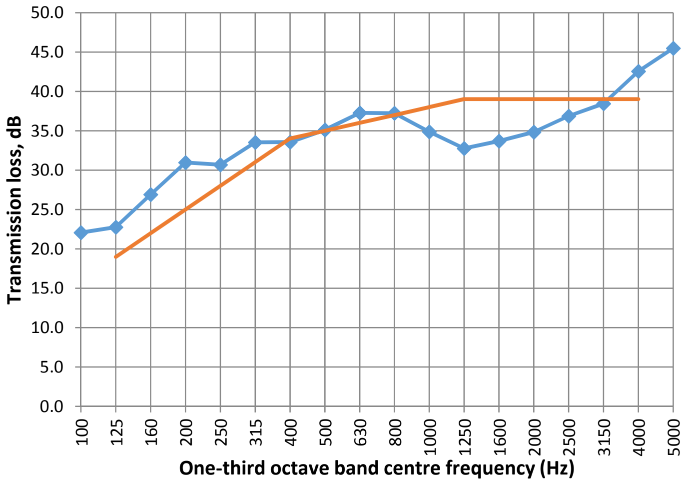
Sound transmission class (STC) in accordance with ASTM E413-10: 32

Transmission Loss According to ISO 15186-1:2003
Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 1: Laboratory measurements

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: External wall 6 of the CFN facility
Description of specimen: 18 mm plywood
90 mm timber frame with 90 mm fibrous insulation
18 mm plywood
Size of sample: All wall ~ 12.5 m²
Mass: Unknown

Frequency, Hz	PI Index (dB)	Repeatability Index (dB)	R_I
100	4.50	0.10	22.1
125	6.00	0.70	22.8
160	6.50	0.20	26.9
200	8.00	0.20	30.9
250	7.60	0.60	30.7
315	6.90	0.50	33.5
400	6.50	0.60	33.6
500	7.10	0.40	35.1
630	9.30	0.90	37.3
800	9.00	0.90	37.2
1,000	8.20	0.40	34.9
1250	7.10	0.60	32.8
1,600	6.70	0.80	33.7
2,000	6.60	0.80	34.8
2,500	6.00	0.60	36.9
3,150	5.00	0.50	38.4
4,000	6.10	0.60	42.6
5,000	6.40	0.60	45.5



Frequency, Hz	Practical Transmission Loss (dB)
125	24.5
250	31.9
500	35.6
1,000	35.3
2,000	35.3
4,000	43

Transmission Loss:
Weighted sound reduction index in accordance with ISO 717-1:2000: 35
Spectrum adaption, C, C_{tr}: -1, -3
Sound transmission class (STC) in accordance with ASTM E413-10: 36

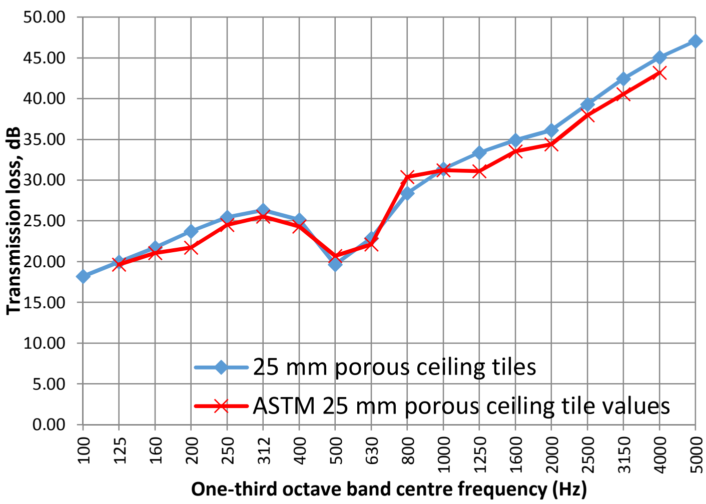
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: T&R Interior Systems CMax 25
Description of specimen: 25 mm glass fibre absorption front
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 1.5 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	84.6	56.4	18.2
125	91.4	60.1	20.0
160	97.0	63.9	21.7
200	97.9	70.5	23.7
250	99.4	70.1	25.5
315	96.7	66.4	26.3
400	98.0	69.9	25.1
500	97.2	73.7	19.7
630	95.2	67.8	22.9
800	94.9	61.9	28.4
1,000	94.1	57.8	31.4
1250	92.0	51.7	33.4
1,600	93.6	50.4	34.9
2,000	92.5	47.2	36.1
2,500	90.9	43.9	39.3
3,150	90.2	40.8	42.4
4,000	87.6	33.7	45.1
5,000	84.9	34.0	47.1



Frequency, Hz	Practical Flanking noise (dB)
250	20.2
250	25.3
500	23.1
1,000	31.5
2,000	37.2
4,000	45.3

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 31
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 33

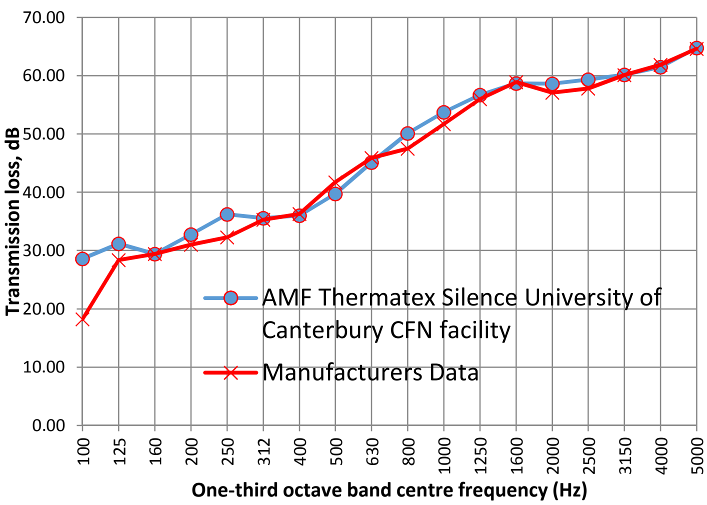
Ceiling Flanking Noise Attenuation According to ASTM E1414-11a
Standard test method for airborne sound attenuation between rooms sharing a common ceiling plenum

Client: Thesis research **Date of test:** [Publish Date]

Test specimen: AMF Thermatex Silence
Description of specimen: 13 mm dense mineral fibre backing
30 mm porous mineral fibre absorption layer
White glass fibre front tissue facing
Square edged
Size of sample: Full ceiling -
Mass: 10.8 kg/m²
Suspended ceiling grid USG Donn DXT 38 mm continuous between rooms
Designation – C, E

Test information: CFN facility at the University of Canterbury
Volume: Source Room – 46.13 m²
Receiving room – 46.66 m²
Partition: Double stud wall with steel adaptor capping– Insitu testing achieves STC/R_w 61
Area of test specimen: 7.1 m x 4.5 m – 31.95 m²
Mount: Ceiling tiles mounted horizontal in USG Donn DXT suspended ceiling grid over both rooms

Frequency, Hz	L_1 Source room (dB)	L_2 Receiving room (dB)	$D_{n,c,w}$ (dB)
100	74.2	40.8	28.6
125	84.1	48.7	31.2
160	87.6	54.9	29.4
200	91.8	55.6	32.7
250	94.0	54.0	36.2
315	93.5	53.9	35.6
400	89.8	50.1	36.0
500	88.5	45.3	39.7
630	87.7	38.8	45.1
800	89.3	35.6	50.1
1,000	89.2	31.9	53.7
1250	89.2	29.1	56.7
1,600	90.8	29.8	58.7
2,000	91.5	29.9	58.7
2,500	91.2	29.3	59.3
3,150	89.2	27.0	60.2
4,000	87.6	23.9	61.5
5,000	86.9	19.3	64.8



Frequency, Hz	Practical Flanking noise (dB)
250	29.9
250	35.1
500	41.8
1,000	54.3
2,000	58.9
4,000	62.6

Transmission Loss:
Weighted suspended-ceiling normalised level difference in accordance with ISO 717-1:2000: 48
Ceiling attenuation class (CAC) in accordance with ASTM E413-10: 48